e-Meeting, BNL, 03/10/11

The Case for Future ep Physics at eRHIC

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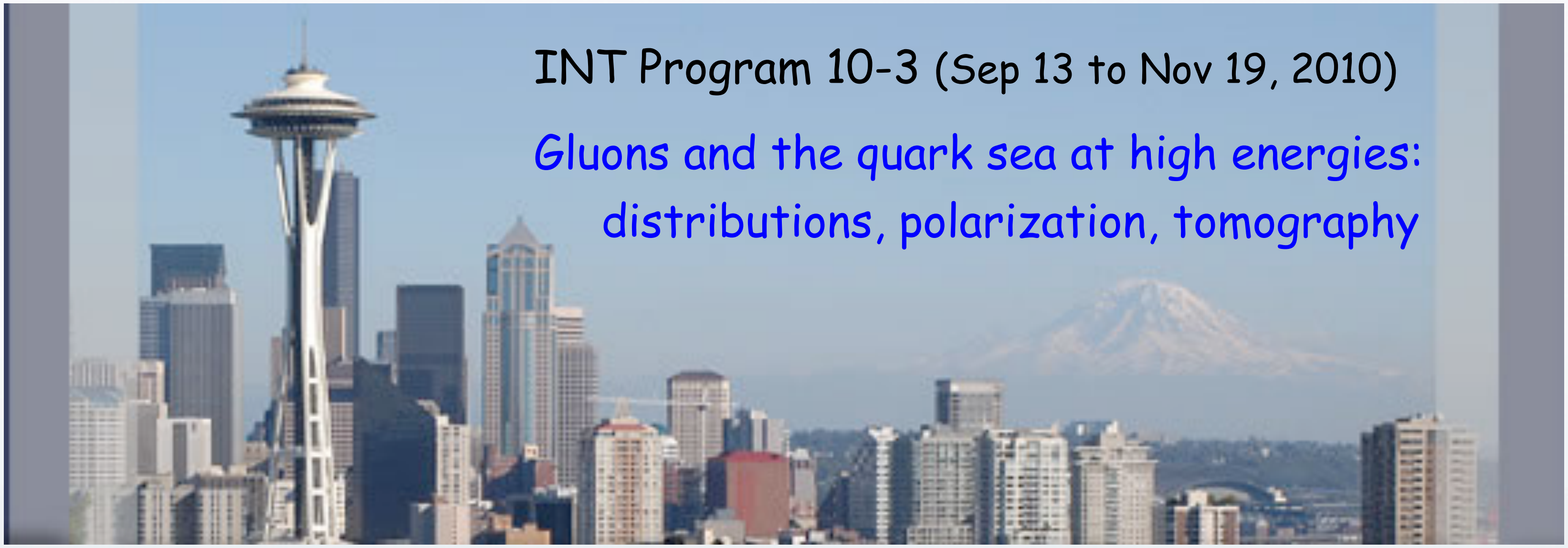


organizers: D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang
convenors: D. Hasch, M.S., F. Yuan (spin & PDFs); M. Burkardt, V. Guzey, F. Sabatie (imaging);
A. Accardi, M. Lamont, C. Marquet (eA); K. Kumar, Y. Li, W. Marciano (beyond SM)

main goal: sharpen the physics case for an EIC for next NSAC long range plan

- identify outstanding open questions in hadronic physics still relevant in 10+ years
- devise key measurements in ep and eA to address these questions
- quantify experimental needs, requirements, and feasibility

this talk: ep physics is a vast field --> concentrate only on the most compelling measurements at a future EIC

detailed write up is currently put together – to appear on the arXiv

main theme: HERA an *unfinished* business

16yrs of data taking leave a rich legacy of knowledge & by now textbook results
(steep rise of F_2; small-x gluons, diffraction, e-w effects, photoproduction, spin structure, ...)

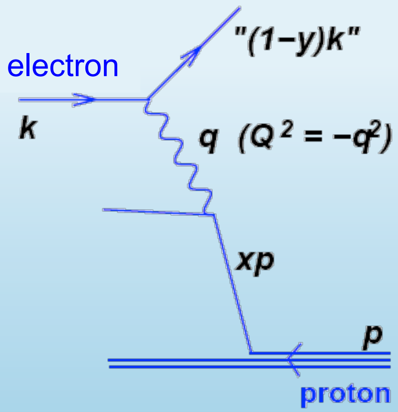
so, what did we miss which is still of interest in 2020+ ?

- spin structure "only" studied in fixed-target regime (HERMES, ...)
- "only" proton beams – neutron structure ? – nuclei ?
- $L = 500\ pb^{-1}$ and variation of E_p not sufficient to really study F_L
- completely unfold flavor & spin structure: JLab12? LHC?
  strangeness & $s - \bar{s}$ asymmetry ? - d/u and the gluon @ large-x ?
- concepts/processes introduced but neither fully explored nor understood:
  GPDs, unintegrated PDFs, diffraction, role of heavy flavors,
  photoproduction, electroweak physics in ep, semi-inclusive processes, ...

considerable overlap with physics agenda of a possible LHeC

Kinematic Coverage

key to eRHIC program: large & *variable* kinematic coverage



recall: DIS kinematics

$$Q^2 = xyS$$

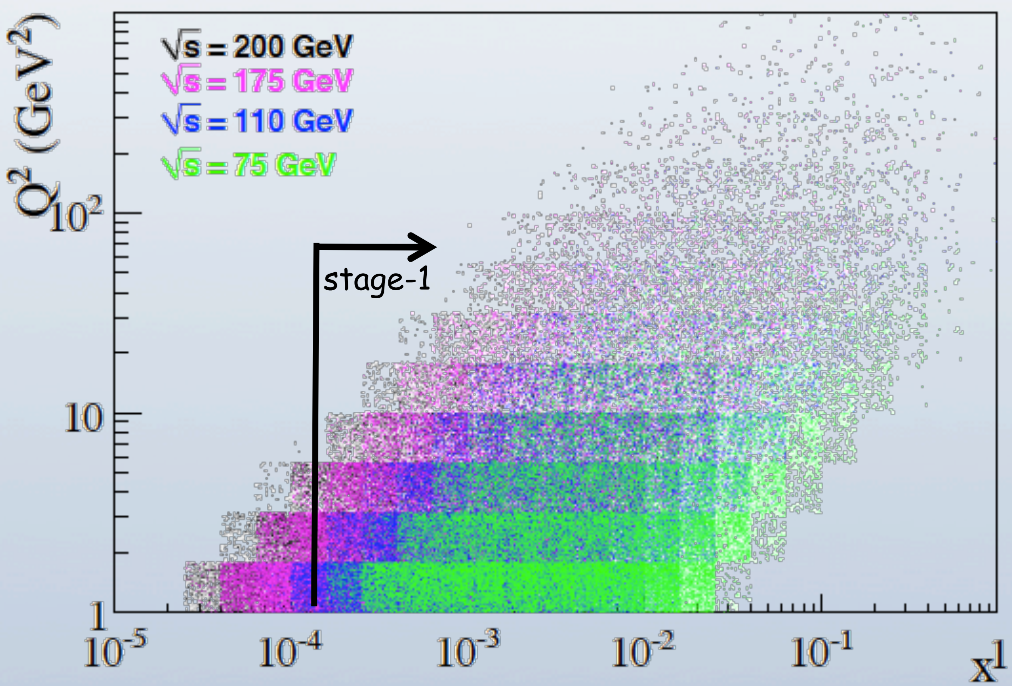
$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot k}$$

Q^2: proton virtuality ↔ resolution $r \sim 1/Q$ at which the proton is probed

x: longitudinal momentum fraction of struck parton in the proton

y: momentum fraction lost by electron in the proton rest frame



eRHIC stage-1:

5x50, 5x100, ..., **5x250**, **5x325**

$\sqrt{S} = 32$ 45 71 81

$x_{\min} \approx 10^{-3}$ 2×10^{-4} 1.6×10^{-4}

small x pol. DIS

← lever arm for F_L →

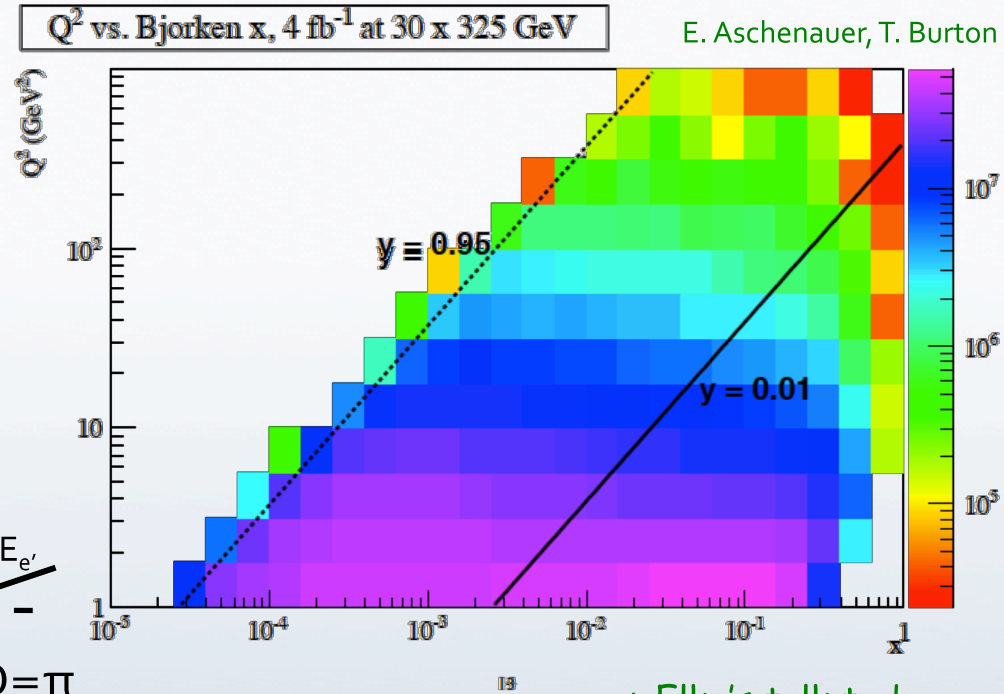
eRHIC: up to 30x325

$$\sqrt{S} = 198$$

$$x_{\min} \approx 2.7 \times 10^{-5}$$

kinematics – a closer look, issues

- find out how low in y we can go
  - increase x,Q^2 coverage for each S
  - more overlap between different S
  - more lever-arm for Q^2 evolution at *fixed* x
  - upper y cut has much less impact

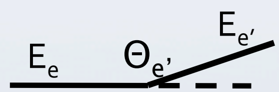


E. Aschenauer, T. Burton

--> Elke's talk today

- tagging of the scattered electron

$$Q^2 = 2E_e E_{e'}(1+\cos\theta_{e'})$$



  - need to detect electrons at forward Θ=π
  - most "severe" for $Q^2 \approx 0$ (photoprod.)

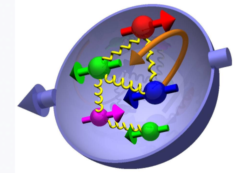
- QED radiative corrections
  - known to be significant at HERA
  - devise strategies to control them i.e., reconstruct true x, Q^2 reliably
  - exploit different methods to reconstruct x,Q^2 ("electron", "Jacquet-Blondel", "combined")

needs to be studied in more detail
but expected to be under good control
Aschenauer, Spiesberger

Monte Carlo tools at hand

OPPORTUNITIES IN INCLUSIVE (UN)POLARIZED DIS

special interest in polarized PDFs



holy grail: proton spin sum - a key measurement at eRHIC ?

A^{+}=0 gauge version

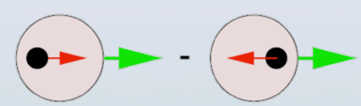
Jaffe, Manohar; Ji; …

$$\boxed{\frac{1}{2}\hbar = \langle P, \frac{1}{2}|J^z_{\mathrm{QCD}}|P, \frac{1}{2}\rangle = \sum_q \frac{1}{2} S^z_q + S^z_g + \sum_q L^z_q + L^z_g}$$

total u+d+s quark spin | gluon spin | angular momentum

"quotable" properties of the nucleon

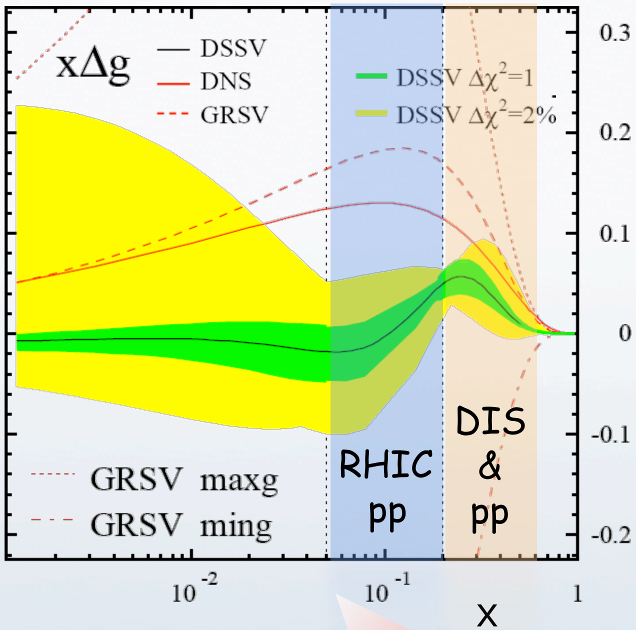
$$\boxed{\Delta f(x) \equiv f_{+}^{N_+}(x) - f_{-}^{N_+}(x)}$$



- requires good knowledge of $\Delta g(x)$ and $\Delta\Sigma(x)$ for a given Q^2
  not to mention orbital angular momentum (OAM)
- low x needed to capture most of the 1st moment integrals, e.g. $S_g = \int_0^1 \Delta g(x) dx$
- however, should not focus too much on 1st moment; want to know full x-dep. !
- picture emerging from present DIS & RHIC data still fuzzy and inconclusive

what can be achieved for Δg?

current status:

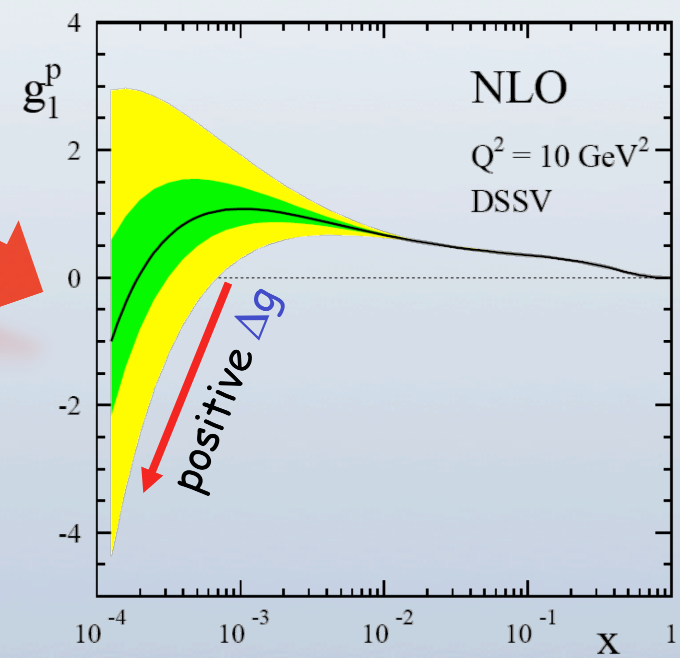


DSSV global fit
de Florian, Sassot, MS, Vogelsang

- low x behavior unconstrained
- no reliable error estimate for 1st moment $\int_0^1 dx\, \Delta g(x,Q^2)$ (entering spin sum rule)
- find $\int_{0.05}^{0.2} dx\, \Delta g(x,Q^2) \approx 0$

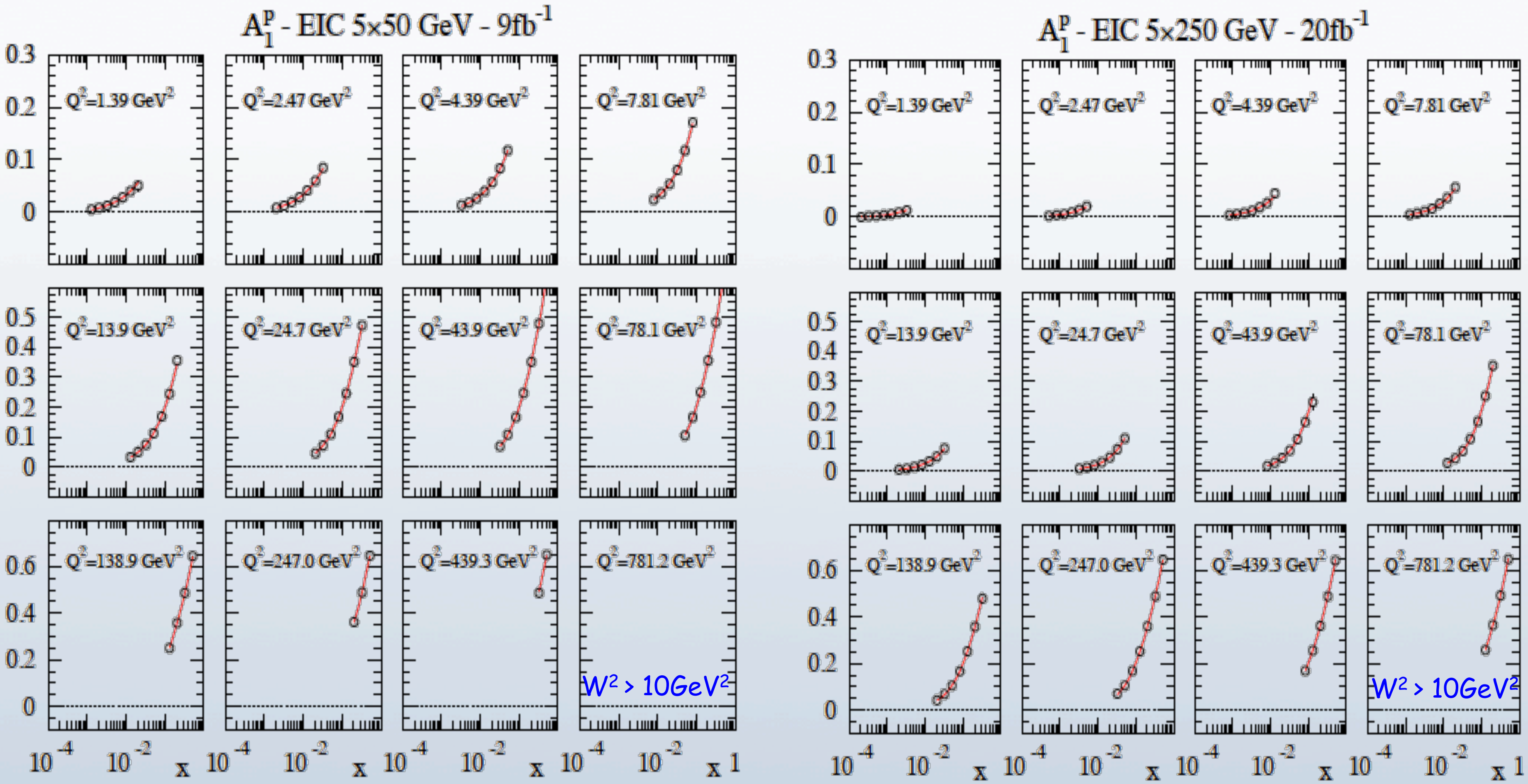
pQCD scaling violations

$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$



polarized DIS @ eRHIC and impact on $\Delta g(x,Q^2)$

strategy to quantify impact: global QCD fits with realistic toy data



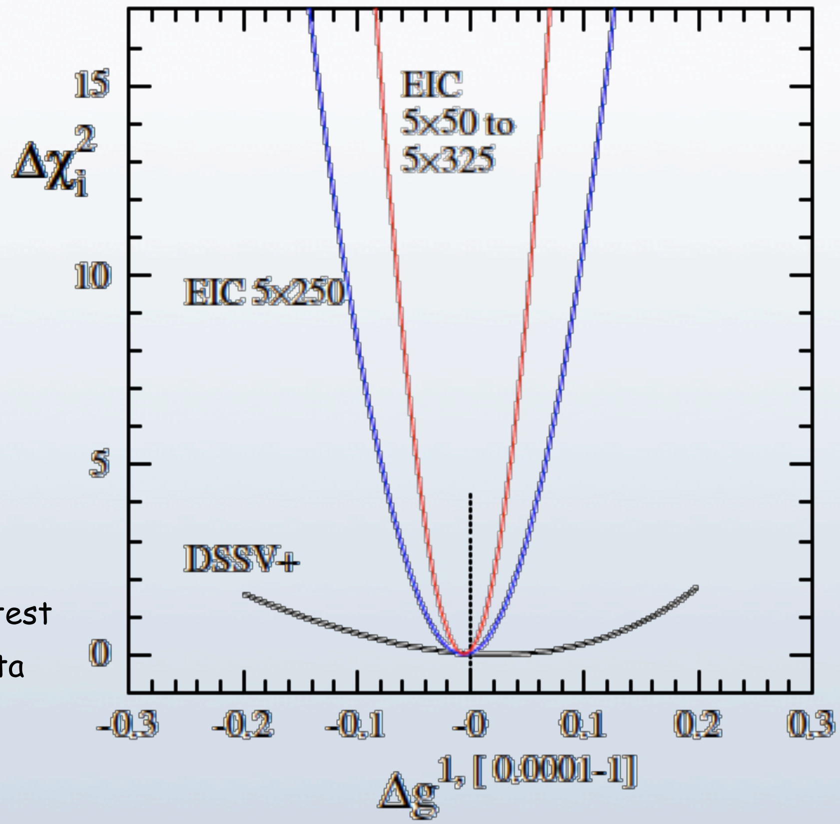
• DIS statistics "insane" after ≈ 1 month of running (errors MUCH smaller than points in plots)

measurements limited by systematics – true for most of ep case

what can be achieved for Δg? – cont'd

how effective are scaling violations already at stage-1 (recall $x_{min} \approx 1.6\times10^{-4}$)

Sassot, MS



DSSV+ includes also latest COMPASS (SI)DIS data (no impact on DSSV Δg)

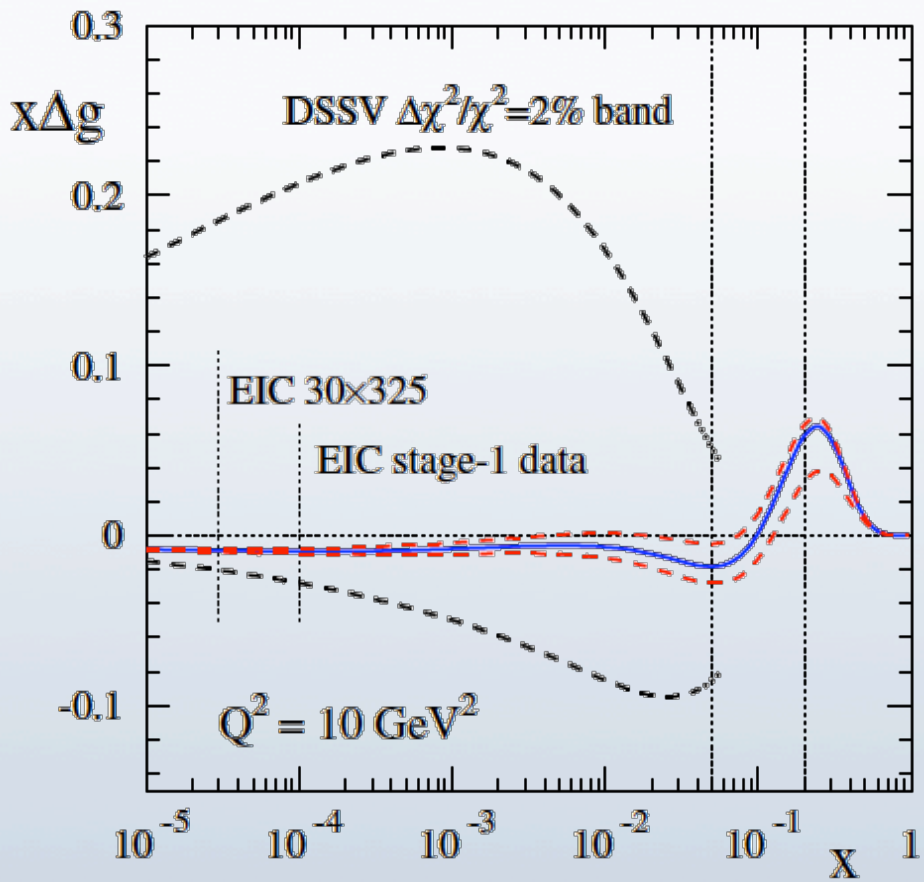
χ^2 profile slims down significantly already for stage-1 (one month of running)

- with 30x325 one can reach down to $x \approx 3\times10^{-5}$ (impact needs to be quantified)

what can be achieved for Δg? - cont'd

what about the uncertainties on the x-shape …

Sassot, MS



golden measurement

✓ unique
✓ feasible
✓ relevant

- even with flexible DSSV x-shape we can now determine $\int_0^1 dx\,\Delta g(x,Q^2)$ to about ± 0.07
- work in progress: try weird x-shapes below x = 10^{-4} to improve/check error estimate

other opportunities in polarized DIS

- in 10+ years the NNLO corrections will be available (certainly needed to match precision of data !) — Moch, Vogt, …
- watch out for surprises at small-x = deviations from DGLAP (expected to set in earlier than in unpol. DIS; showing up as tension in global fits (?)) — Bartels, Ermolaev, Ryskin; Greco, Troyan; …
- strong coupling from scaling violations ? (needs to be worked out / quantified)
- Bjorken sum rule: $\int_0^1 dx\,[g_1^p(x,Q^2) - g_1^n(x,Q^2)] = \frac{1}{6} C_{\mathrm{Bj}}\,[\alpha_s(Q^2)]\; g_A$
  - C_{Bj} known to $O(\alpha_s^4)$ — Kodaira; Gorishny, Larin; Larin, Vermaseren; Baikov, Chetyrkin, Kühn, …
  - but not a tool to determine α_s (1% change in α_s translates in 0.08% change of Bj sum)
  - experimental challenge: effective neutron beam (^{3}He), very precise polarimetry, …
  - theor. motivation for precision measurement: **Crewther relation**

non-trivial relation of two seemingly unrelated quantities

$$\text{Adler function } D(Q^2) \text{ in } e^+e^- \;\xleftrightarrow[\text{deviation from exact conformal symmetry}]{\sim 1 + \frac{\beta(\alpha_s)}{\alpha_s} K(\alpha_s)}\; \text{Bj sum } C_{Bj}(Q^2) \text{ in DIS}$$

unpolarized DIS at eRHIC

- precision data for F_2 may help to resolve some issues with old fixed target data (nice to have, but only "incremental" with little impact; cannot beat HERA at small x)

- **longitudinal structure function F_L** - basically missed at HERA (fixed E_e, E_p)

interesting for several reasons:

- hard to get; recall $\sigma_r = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$

$$y = Q^2/xS$$
$$Y_+ = 1 + (1-y)^2$$

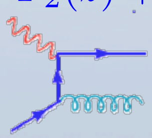
→ contributes mainly at large y (= lowest x for any given Q^2)

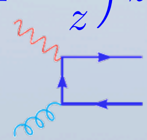
strategies:

  - indirect measurement from deviation of σ_r from "F_2 only fit"
  - slope of y^2/Y_+ for different S at fixed x and Q^2 **strength of eRHIC**

- F_L starts only at $O(\alpha_s)$ (due to helicity conservation)

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2(z) + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) zg(z) \right]$$

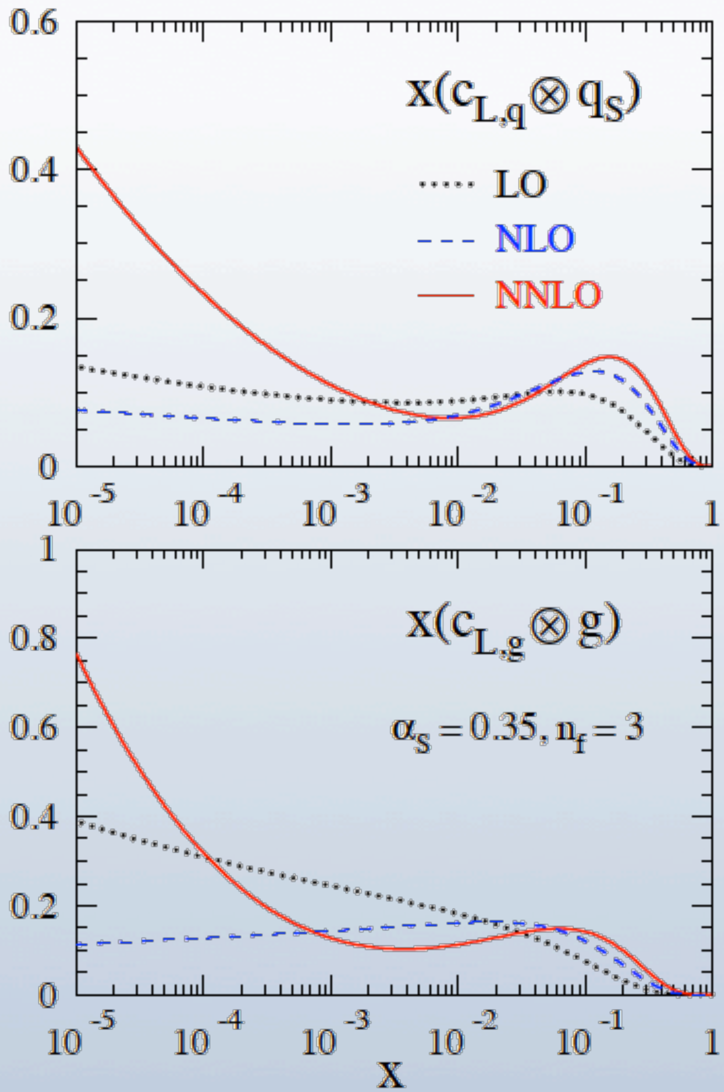




this is the LO expression

longitudinal structure function F_L - cont'd

best motivation for a precise measurement at eRHIC in 10+ years
is not so much to determine the gluon density but to understand pQCD series



- known up to three loops (NNLO)

  Moch, Vermaseren, Vogt

- leading small x term $\sim \ln x$
  appears first at NNLO
  (very different from the "usual" F_2)

- sensitivity to small x term best
  at lowish Q^2 values (few GeV^2)

1st feasibility study for $\sigma_r = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$

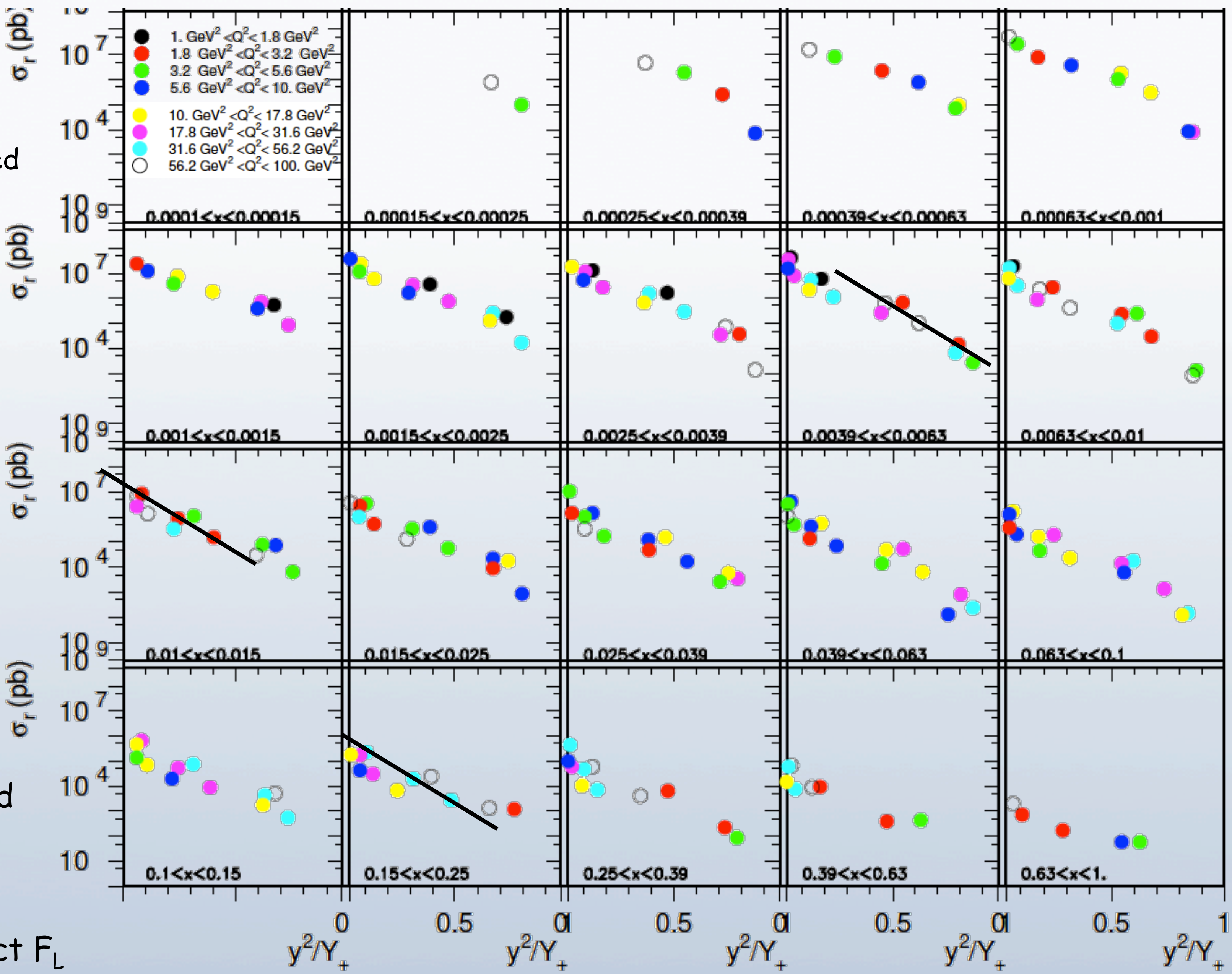
E. Aschenauer

5x50 - 5x325
running combined

F_L “slopes”
(examples)

TO DO:

refine method
&
test how well
we can extract F_L

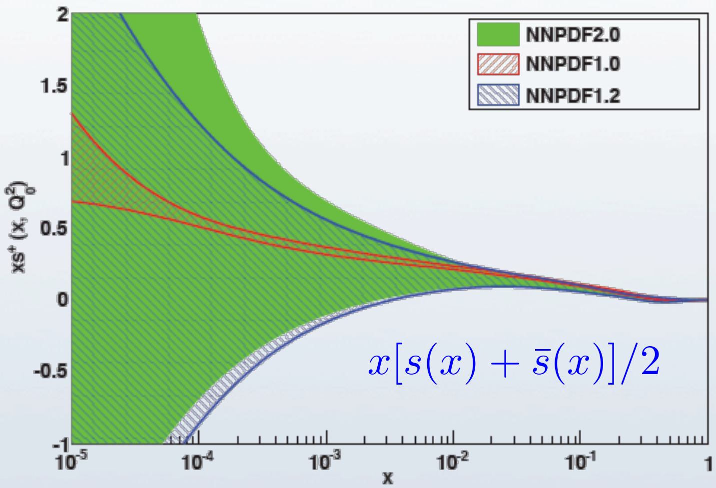


SEMI-INCLUSIVE DIS & FLAVOR SEPARATION

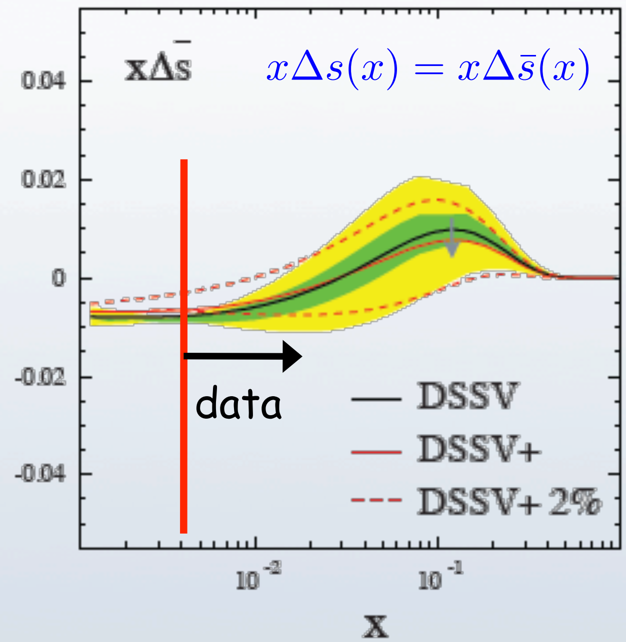
selected open issues in flavor structure

strangeness is one of the least known quantities in hadronic physics
– both unpolarized and polarized – where significant progress is difficult w/o eRHIC

NNPDF collaboration



DSSV (incl. latest COMPASS data)

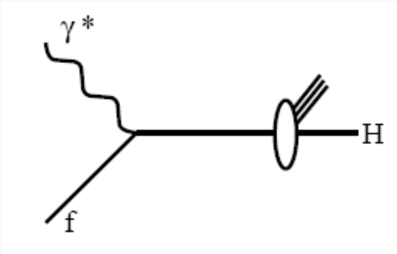


- substantial uncertainties
- known issues with HERMES data at large x
- **hot topic:** $s(x) - \bar{s}(x)$

- **surprise:** Δs small & positive from SIDIS data
- but 1st moment is negative and sizable due to "constraint" from hyperon decays (F,D)
  (assumed SU(3) symmetry debatable M. Savage)
- drives uncertainties on ΔΣ (spin sum)

we really need to determine it better ! (including their u,d quark colleagues)

idea: flavor separation with semi-inclusive DIS

at LO: 

$$d(\Delta)\sigma^H \simeq \sum_{q=u,\bar{u},\dots,\bar{s}} (\Delta)q(x,Q^2)\; D_q^H(z,Q^2)$$

extra weight for each quark

allows for full flavor separation if enough hadrons are studied

actual analysis of data requires NLO QCD where x, z dependence is non-trivial

relevant quantities/measurements:

- (un)polarized SIDIS cross sections (we don't want to study asymmetries anymore at eRHIC)
- for u, ubar, d, dbar, s, sbar separation need H = π^+, π^-, K^+, K^- (nice to have more)

complications/additional opportunities:

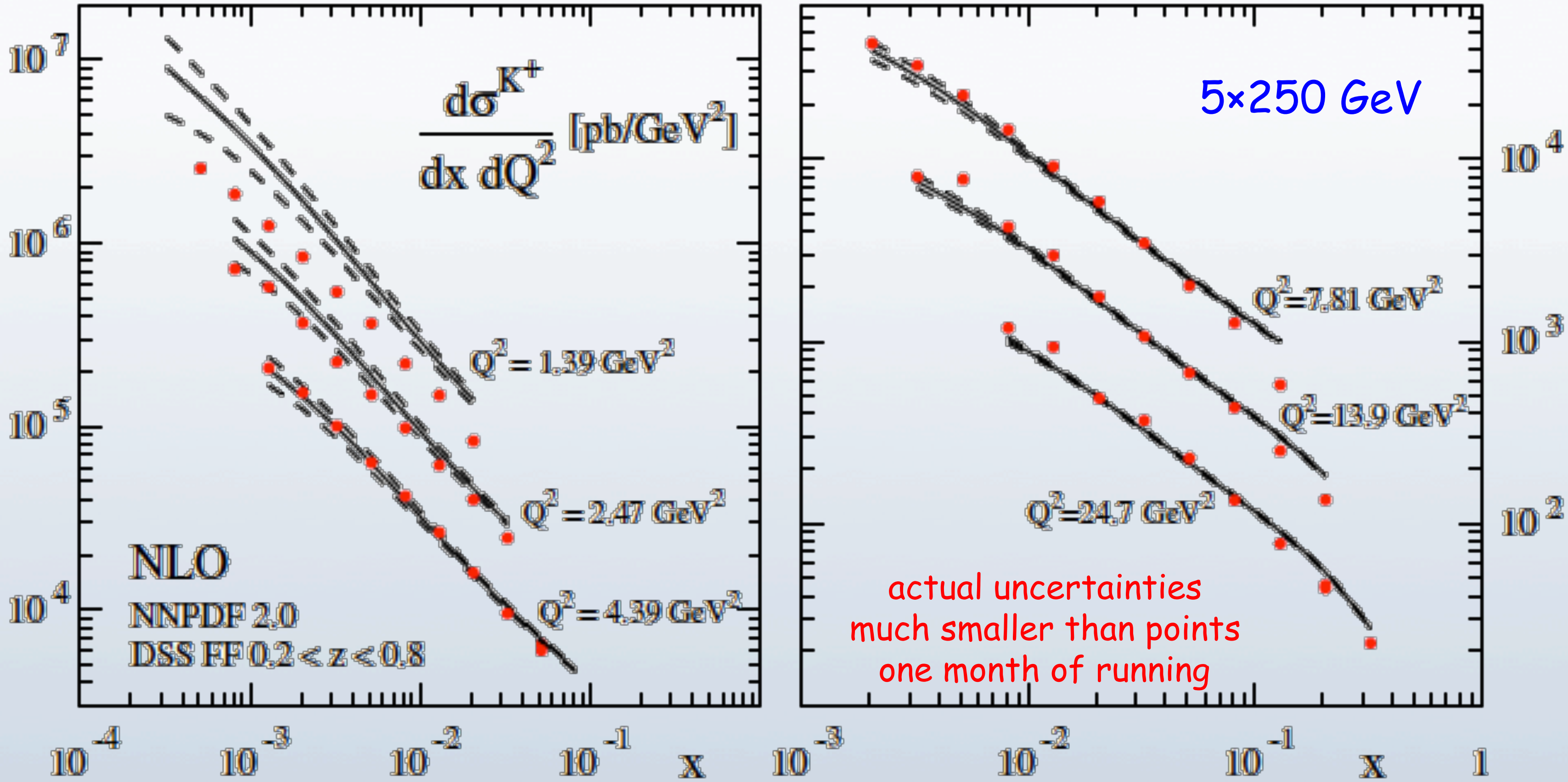
- PDF information entangled with fragmentation functions
- should be not a problem: already known pretty well (DSS - de Florian, Sassot , MS)
  more data (Belle, BaBar, RHIC, LHC, ...)

1st studies done for charged kaons

Aschenauer, MS

compute K+ yields at NLO with 100 NNPDF replicas

z integrated to minimize FF uncertainties (work in progress)

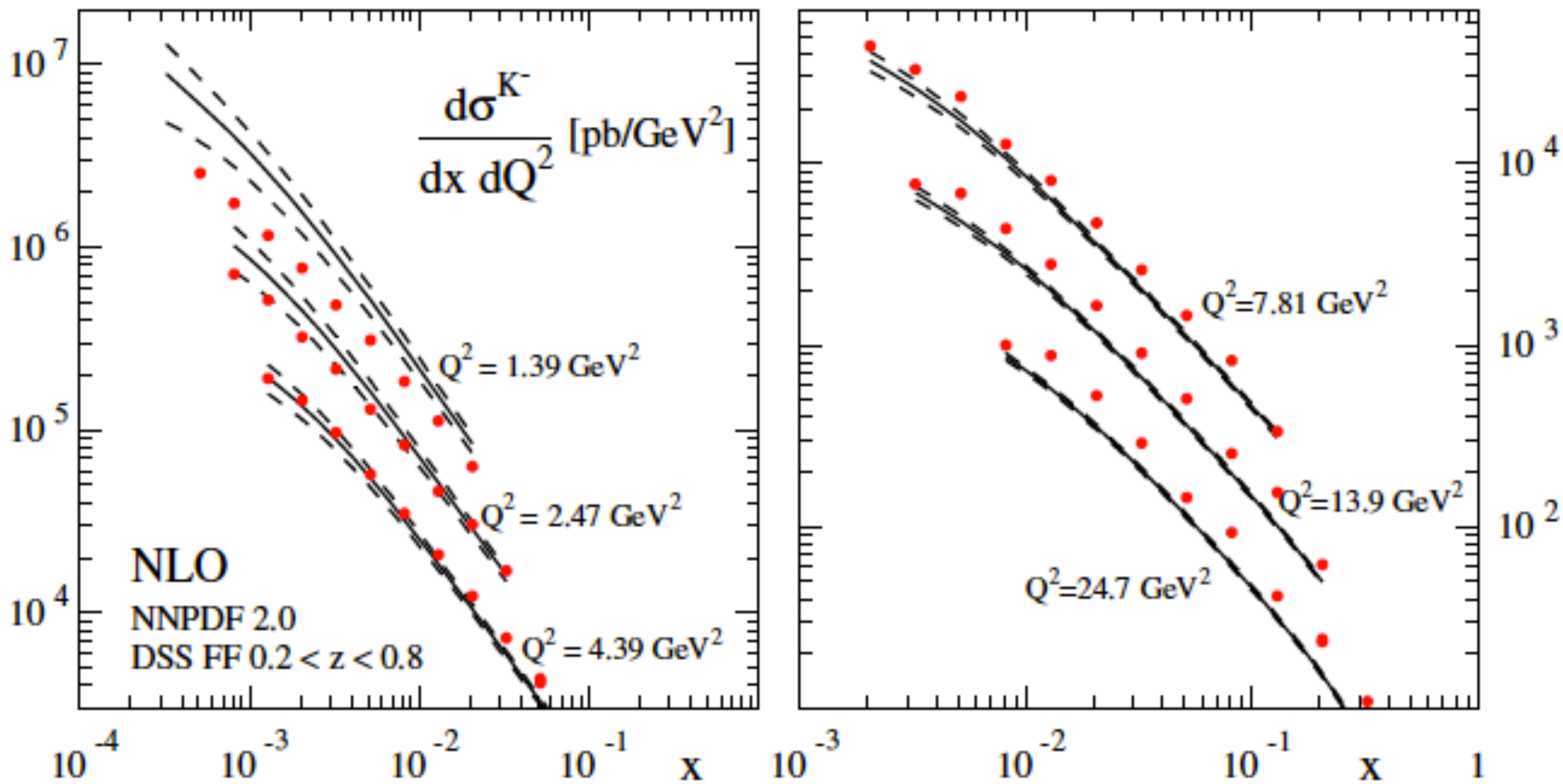


PYTHIA agrees very well (despite ***very*** different hadronization model)

--> confidence that we can use MC to estimate yields & generate toy data

kaon studies - cont'd

how about K^- (relevant for $s - \bar{s}$ separation)



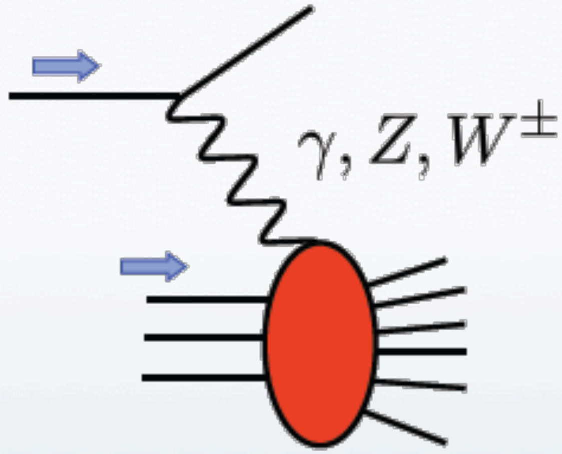
next step: assess impact of data on PDFs with "reweighting method"
(using full set of stage-1 energies: 5×50 – 5×325)

Giele, Keller; NNPDF

in progress: include also $\pi^{\pm}$; polarized SIDIS and impact on global fit

Charged & Neutral Current Probes

main objective / why interesting



at high enough Q^2 electroweak probes become relevant

- **neutral currents** (γ, Z exchange, γZ interference)
- **charged currents** (W exchange)

parameterized by new structure functions which probe combinations of PDFs different from photon exchange
--> **flavor decomposition without SIDIS, e-w couplings**

hadron-spin averaged case: studied to some extent at HERA (limited statistics)

hadron-spin difference:

contains e-w propagators and couplings

Wray; Derman; Weber, MS, Vogelsang;
Anselmino, Gambino, Kalinowski;
Blumlein, Kochelev; Forte, Mangano, Ridolfi; ...

$$\frac{d\Delta\sigma^{e^{\mp},i}}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\left[\pm y(2-y)x\hat{g}_1^i - (1-y)\hat{g}_4^i - y^2 x\hat{g}_5^i\right] \quad \mathrm{i} = \mathrm{NC}, \mathrm{CC}$$

unexplored so far – unique opportunity for eRHIC

what can be learned

in the parton model (for simplicity)

NC:

$$\left[g_1^{\gamma}, g_1^{\gamma Z}, g_1^{Z}\right] = \frac{1}{2}\sum_q \left[e_q^2, 2e_q g_V^q, (g_V^q)^2 + (g_A^q)^2\right] (\Delta q + \Delta\bar{q})$$

$$\left[g_5^{\gamma}, g_5^{\gamma Z}, g_5^{Z}\right] = \frac{1}{2}\sum_q \left[0, e_q g_A^q, g_V^q g_A^q\right] (\Delta q - \Delta\bar{q})$$

CC:

$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c)$$

$$g_1^{W^+} = (\Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c})$$

$$g_5^{W^+} = (\Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c})$$

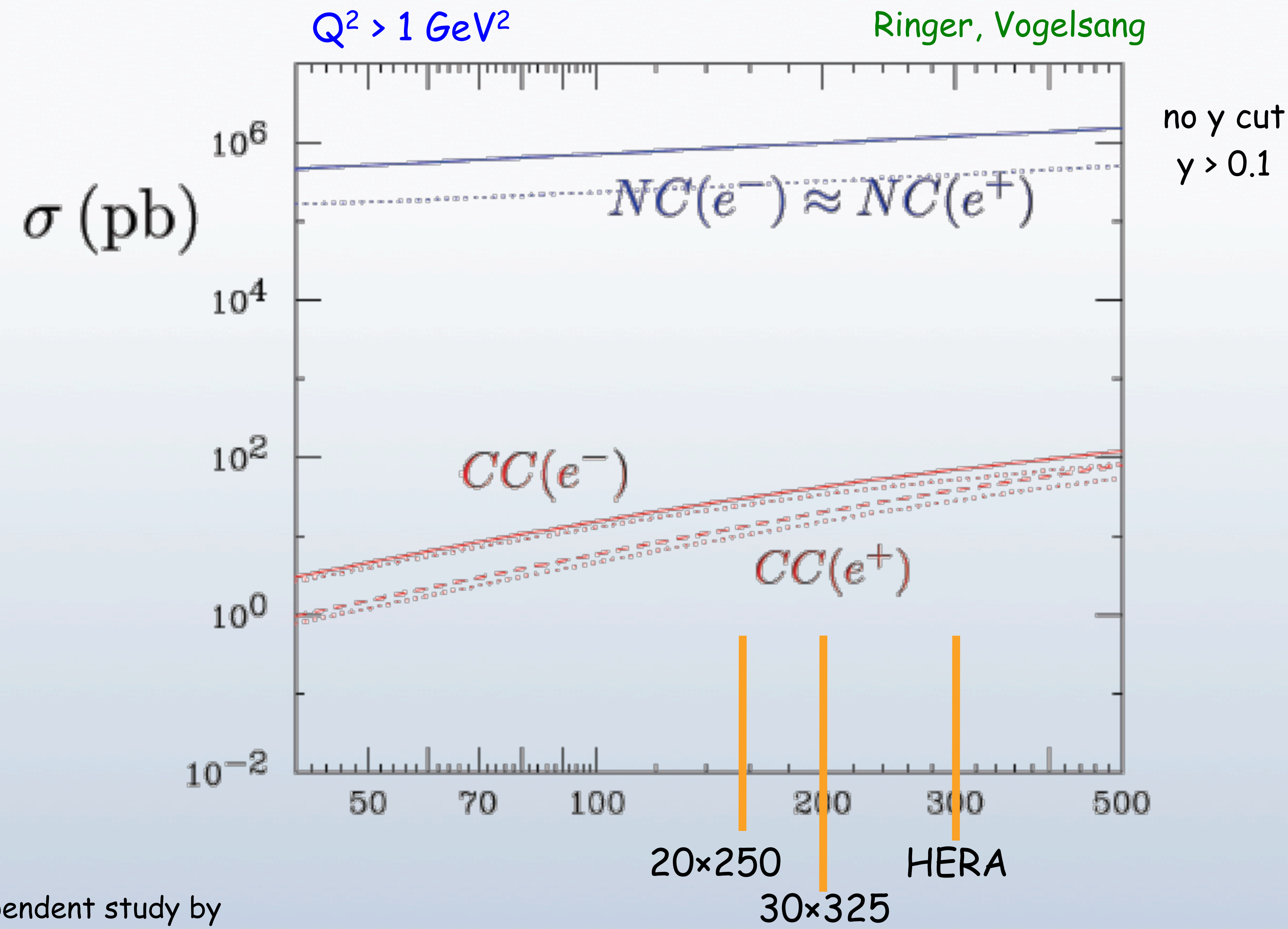
$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c)$$

requires a positron beam

- NLO QCD corrections all available
- can be easily put into global QCD analysis
- enough combinations for a flavor separation (no fragmentation)

de Florian, Sassot; MS, Vogelsang, Weber;
van Neerven, Zijlstra; Moch, Vermaseren, Vogt

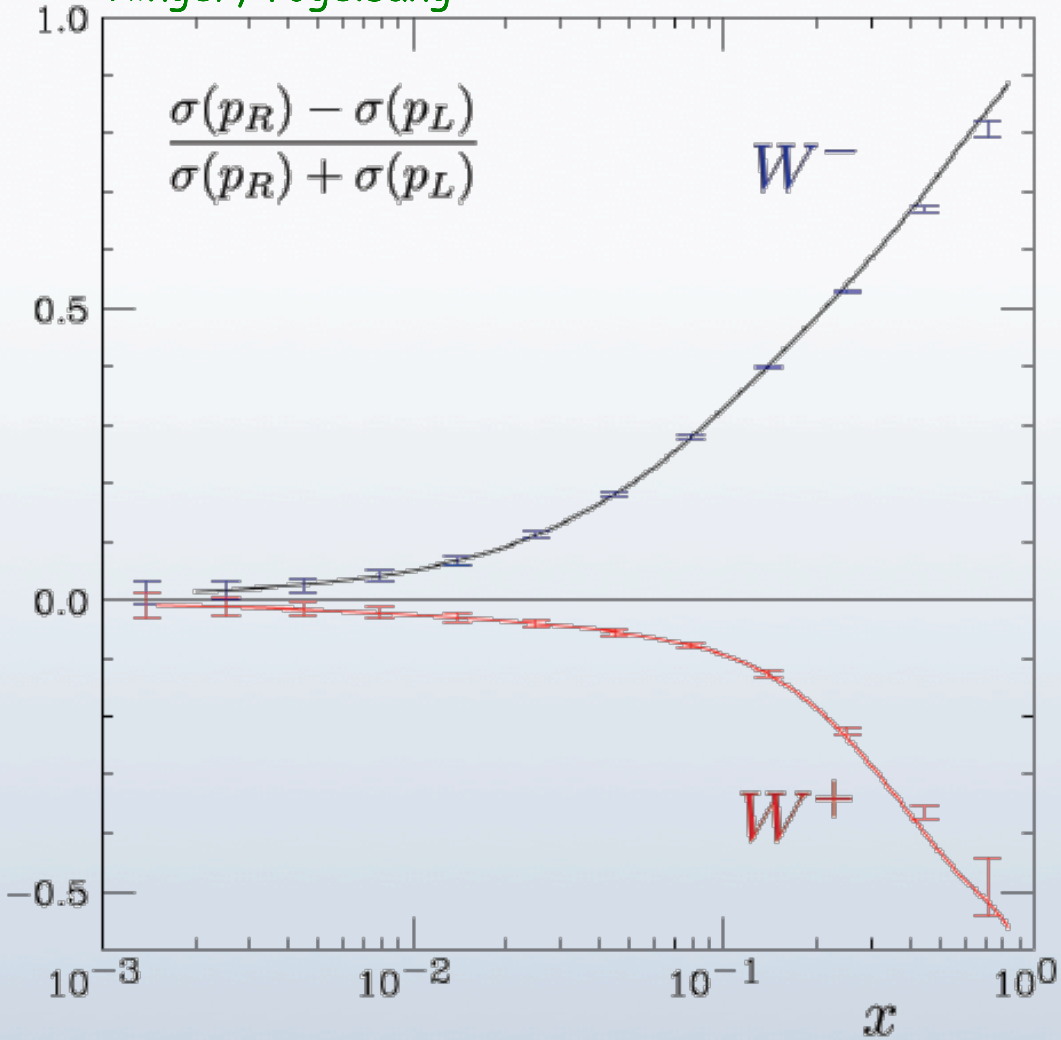
feasibility – 1st exploratory studies



2nd independent study by
Kumar, Riordan, Deshpande, Taneja, Paschke
detailed comparison under way

feasibility - cont'd

Ringer, Vogelsang



20 × 250 GeV

$Q^2 > 1$ GeV^2

$0.1 < y < 0.9$

10 fb^{-1}

DSSV PDFs

very promising!

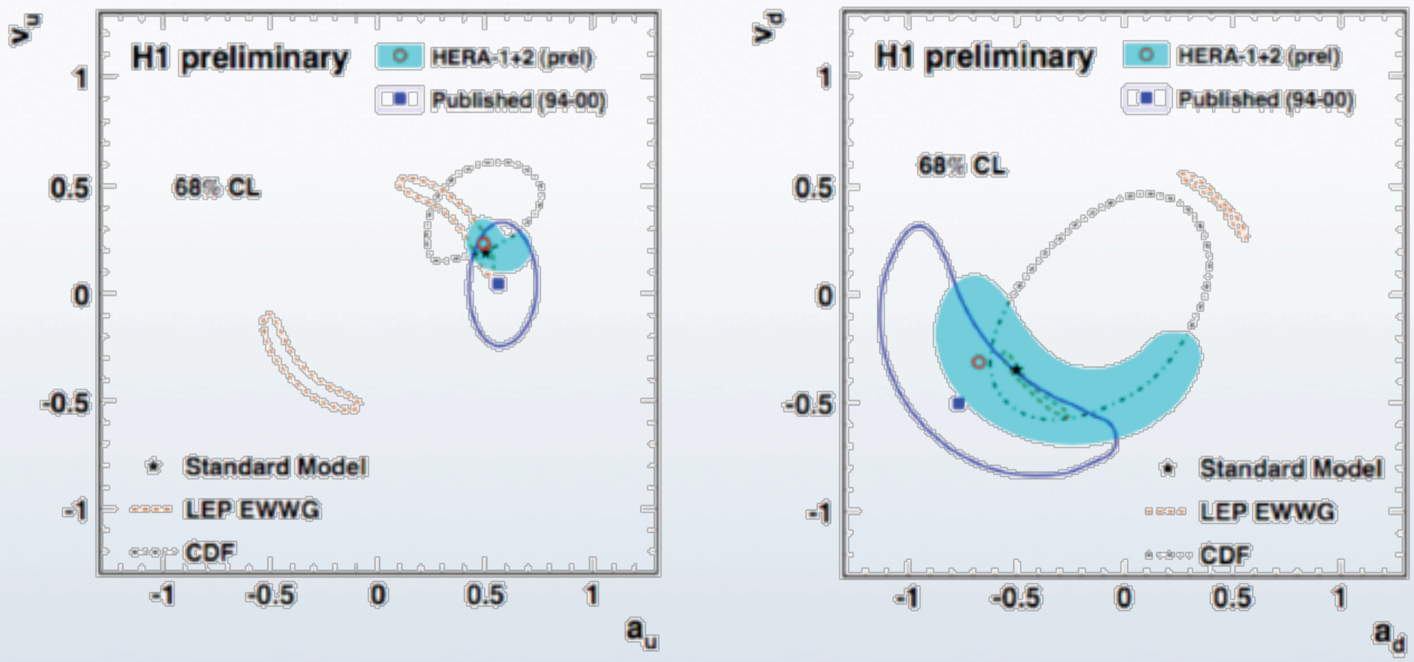
even doable with
5x250 GeV

impact on global fits
to be quantified

$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta\bar{d} + \Delta\bar{s})}{(u+c) + (1-y)^2(\bar{d}+\bar{s})} \quad A^{W^+} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta\bar{u} + \Delta\bar{c})}{(1-y)^2(d+s) + (\bar{u}+\bar{c})}$$

other avenues to be explored further

- accessing fundamental electroweak parameters at an ep collider



a_q mainly constrained by $xF_3^{\gamma Z}$

v_q mainly constrained by F_2^{Z}

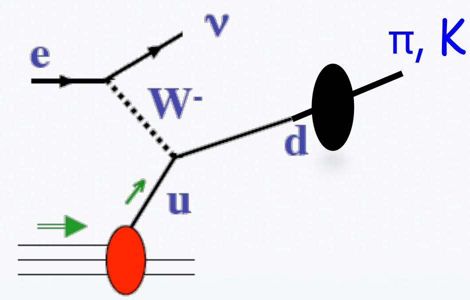
Can we do better than HERA ? What does it take (energy, luminosity)?

needs to be investigated

(prominently featured in LHeC case)

other avenues to be explored further - cont'd

- SIDIS through e-w boson exchange



some studies available from “Future Physics at HERA” workshops:

Maul, Contreras, Ihssen, Schafer; Contreras, De Roeck, Maul

(based on PEPSI Monte Carlo)

TO DO: re-do for eRHIC kinematics

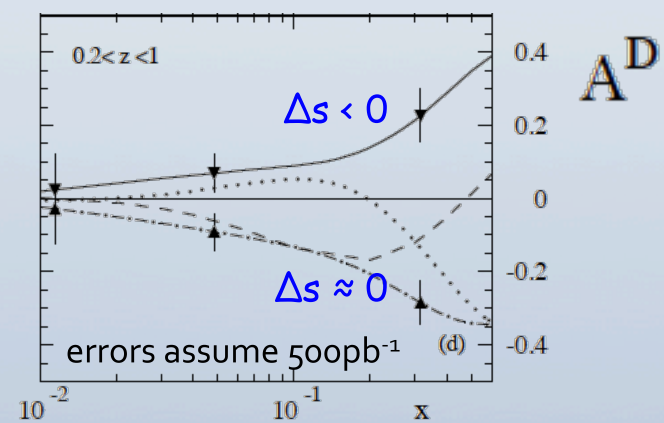
- CC charm production as a probe of strangeness

idea: at $O(\alpha_s^0)$ $W^+ s' \to c$ $s' \equiv |V_{cs}|^2 s + |V_{cd}|^2 d$

at $O(\alpha_s^1)$ $W^+ g \to c\bar{s}'$ can potentially spoil sensitivity to strangeness

also, need to keep full dependence on charm mass in EIC kinematics

- NLO available (pol + unpol) Kretzer, MS
- again, studies performed for HERA
- gluon channel suppressed for z > 0.2 in D meson production

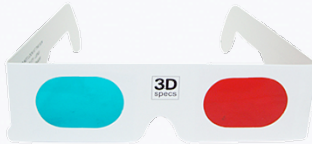


TO DO: exhume codes & re-do for eRHIC

Towards 3D-Imaging of the Proton

two kinds of "3D images"

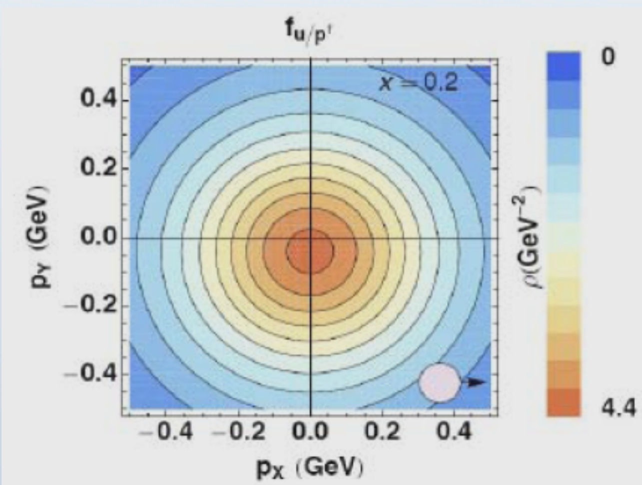
goal: going beyond longitudinal momentum structure



TMDs

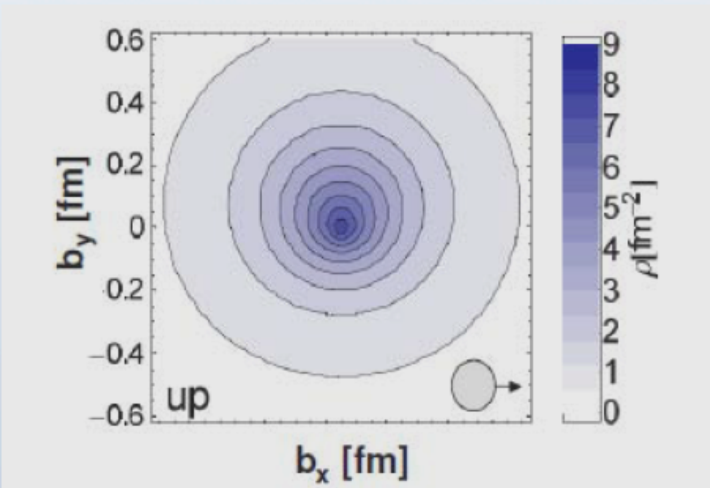
GPDs

2+1 D picture in **momentum space**



Bacchetta, Conti, Radici

2+1 D picture in **impact-parameter space**



QCDSF collaboration

transverse structure: momentum vs. position

relativistic system/uncertainty principle: can localize only in *two* dimensions

TMDs

- intrinsic transverse motion
- spin-orbit correlations = indicator of OAM
- role of gluons "accompanying" partons (Wilson lines or gauge links)
- non-trivial factorization
- matching between small k_T (TMDs) and large, perturbative k_T (twist-3 parton correl.)

GPDs

- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- "dipole model" in small x (large Q^2) limit

gluon and sea distributions largely unknown -> eRHIC

no direct, model-indep. connection known between TMDs and GPDs

average transverse mom. and position *not* Fourier conjugates:

average transv. mom <---> position difference

transv. mom. transfer <---> average position

"high level connection" through Wigner phase space distr. $W(x, k_T, b_T)$

accessing TMDs in SIDIS

- many observables possible in lp -> lhX if intrinsic k_T included and Φ kept
  e.g. "left-right asymmetries" in the direction of produced hadron
- seen at HERMES and COMPASS (but mainly valence quark region & large uncertainties)

SIDIS cross section:

Kotzinian; Mulders, Tangermann; Boer, Mulders. ...

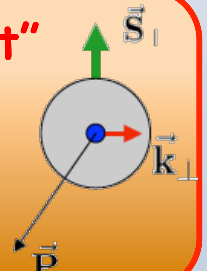
$$d\sigma^h(x, Q^2, z, P_T^h, \phi, \phi_S, \lambda) = d\sigma_{UU} + \cos 2\phi \, d\sigma_{UU} + S_L \sin 2\phi \, d\sigma_{UL} + \underbrace{\lambda S_L d\sigma_{LL}}_{\Delta q \otimes D}$$

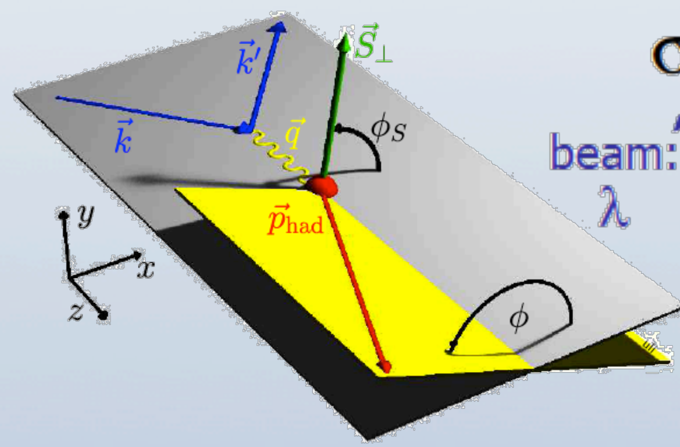
$$+ S_T \left[\sin(\phi + \phi_S) d\sigma_{UT} + \underbrace{\sin(\phi - \phi_S) d\sigma_{UT}}_{f_{1T}^{\perp} \otimes D} + \sin(3\phi - \phi_S) d\sigma_{UT}\right]$$

$$+ \lambda S_T \cos(\phi - \phi_S) d\sigma_{LT} + \frac{1}{Q} \cdots$$

$f_{1T}^{\perp} \otimes D$ **"Sivers effect"**

correlation of transverse spin of proton with k_T of unpolarized quark





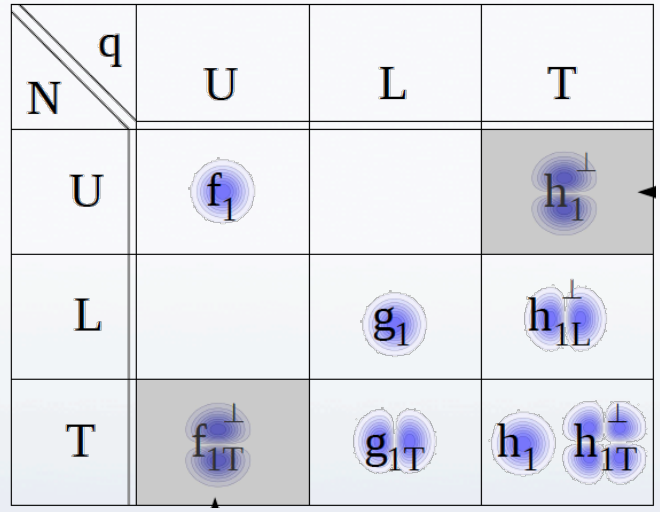
σ_{XY}

beam: λ

target: S_L, S_T

TMDs @ eRHIC

figure taken from B. Musch



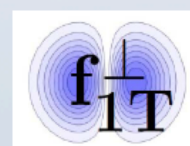
with eRHIC we will measure the entire zoo of TMD functions

(plus additional functions for fragmentation)

difficult to digest & sell to NP community

--> focus on unpolarized f_1 and Sivers function:

$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S}\cdot(\hat{\mathbf{P}} \times \mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$



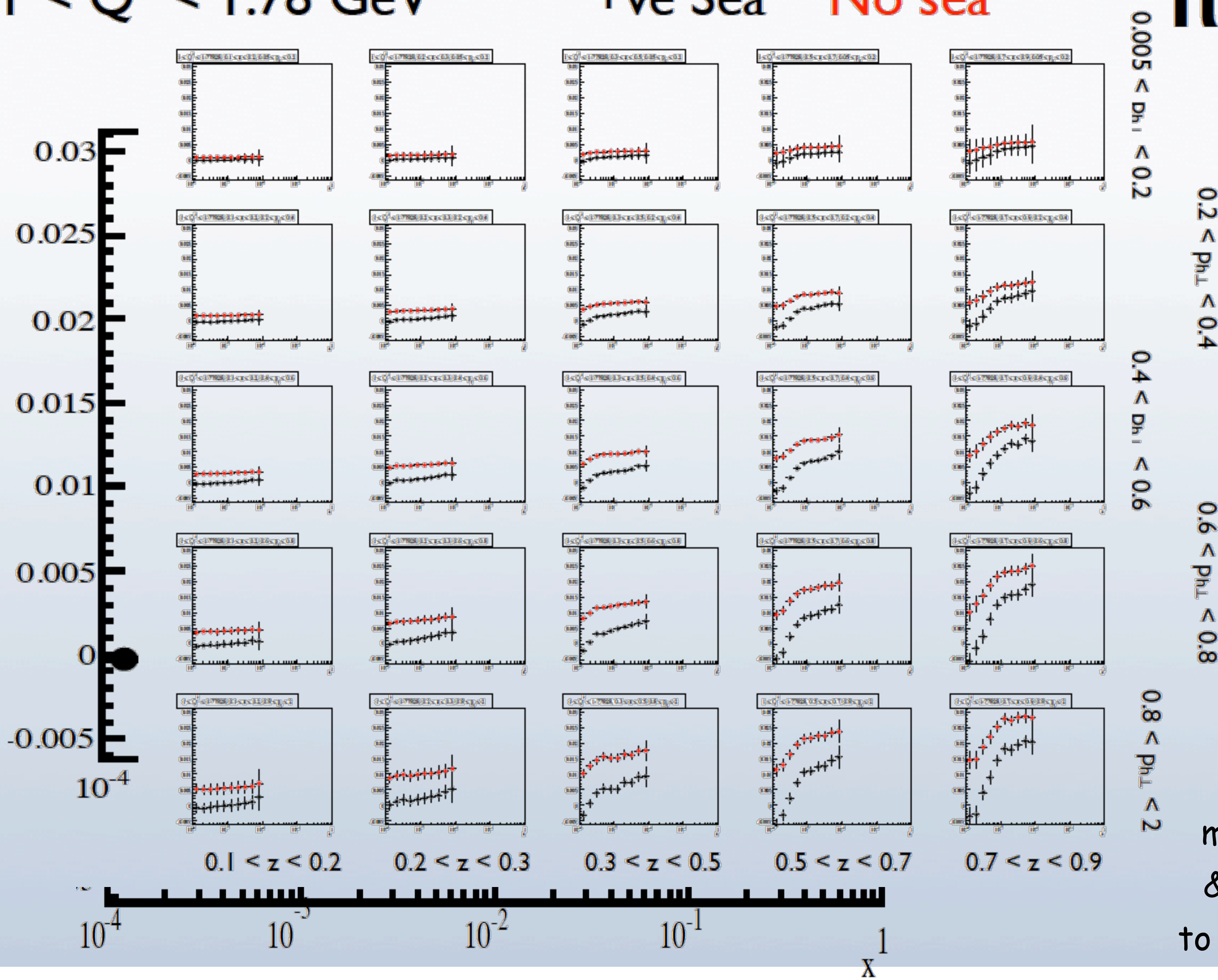
k_T dep. gluon plays prominent role at small x
rather direct access to saturation scale $Q_s(x)$
(e.g. through dijet correlations in eA)

access to 3D imaging in momentum space
non-trivial role of Wilson lines
role of spin-orbit correlations & OAM

Sivers TMD @ eRHIC: 1st feasibility study

T. Burton

$1 < Q^2 < 1.78$ GeV^2 +ve Sea No sea π^+

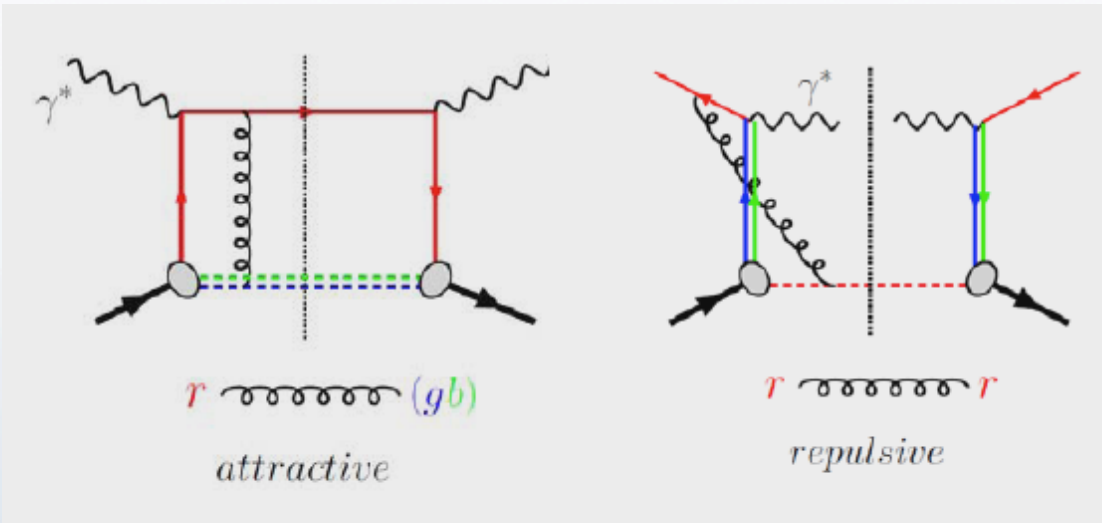


5 x 250 GeV
20 fb^{-1}

multi-dim. binning & Q^2 values up to to 100 GeV^2 possible

TMDs: physics of Wilson lines

profound consequence of gauge invariance: colored partons “surrounded” by gluons (technically realized by Wilson lines)



$$f_{1T}^{\perp \mathrm{SIDIS}} = -f_{1T}^{\perp \mathrm{DY}}$$

Sivers fct. has **opposite sign** when gluons couple “after” quark scatters (SIDIS) or “before” quark annihilates (DY)

(and would be zero without gluons)

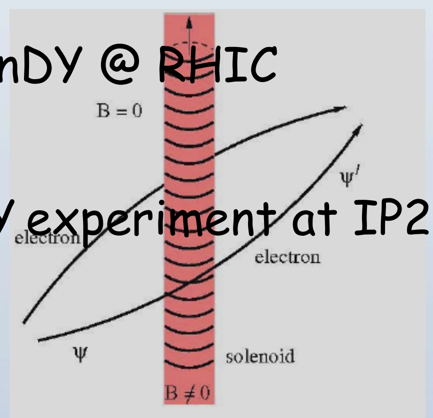
upcoming: AnDY @ RHIC

rough analogy:

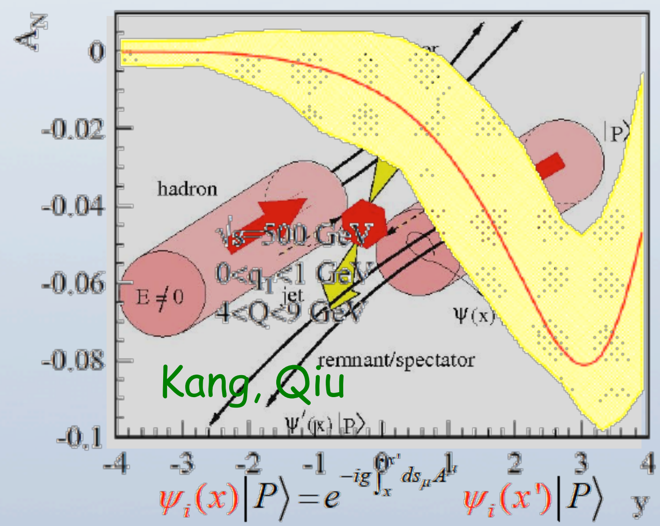
P. Mulders

new dedicated DY experiment at IP2

importance of phases in physics



$$\psi' = e^{ie\int ds.A}\psi$$

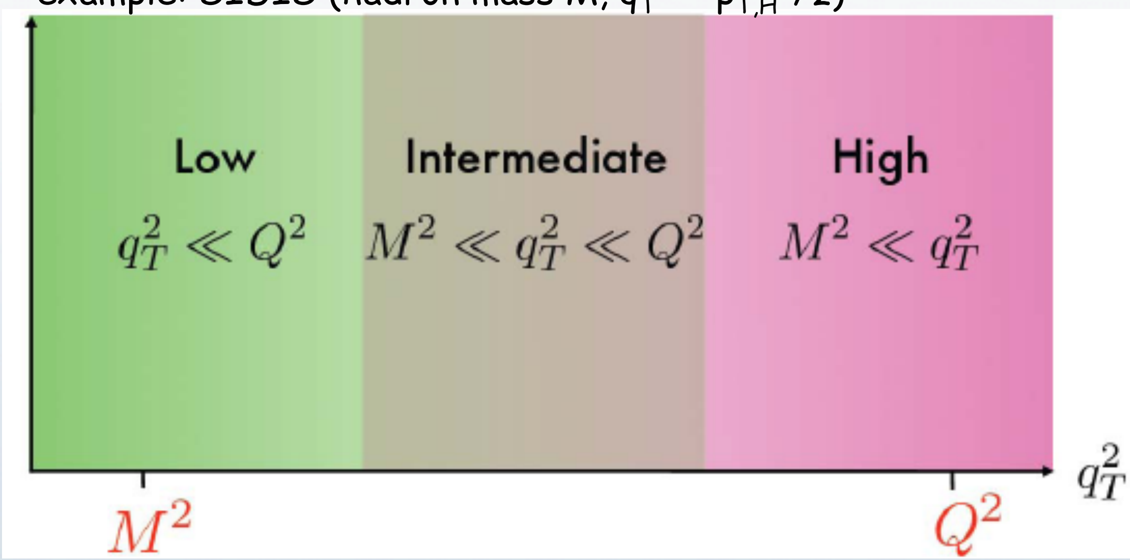


$$\psi_i(x)|P\rangle = e^{-ig\int_x^{x'} ds_\mu A^\mu}\psi_i(x')|P\rangle$$

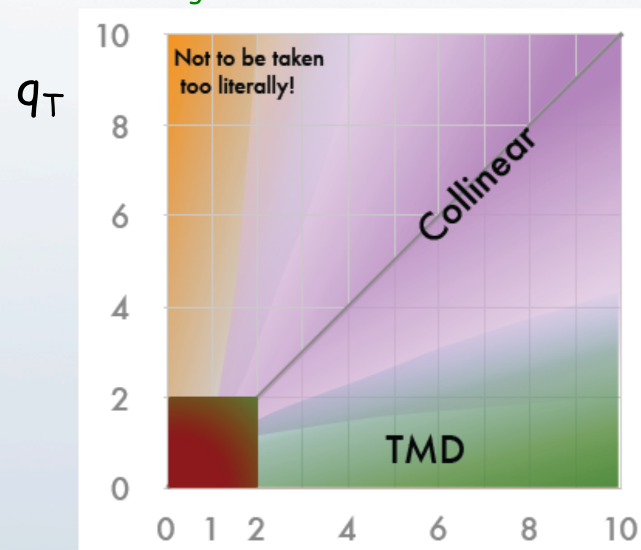
matching low and high p_T physics

- TMDs encode physics for small transverse momenta (or p_T differences) and $Q^2 \gg p_T$
- if p_T is large, it can be treated perturbatively
- no sharp boundary between "intrinsic" and "radiative" p_T --> **matching region**

example: SIDIS (hadron mass M, $q_T^2 \approx p_{T,H}^2/z$)

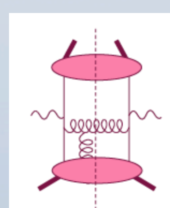


figures taken from A. Bacchetta



TMD factorization

collinear factorization



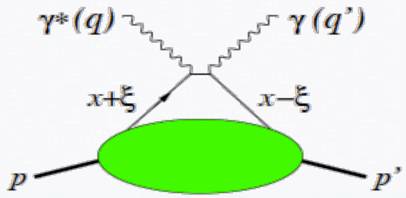
twist-3 parton-parton correlation

the leading high-p_T part should match with the p_T tail of the TMD

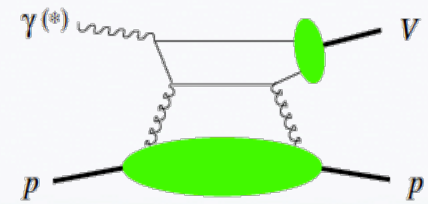
Collins, Soper, Sterman;
Ji, Qiu, Vogelsang, Yuan

GPDs: access to transverse position

need to measure & study **exclusive processes**:

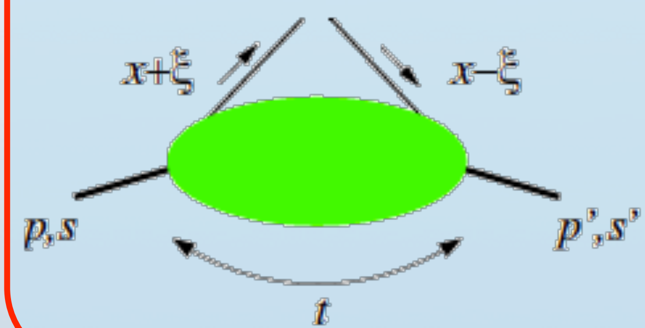


- deeply virtual Compton scattering (DVCS)



- exclusive meson production

- generalized parton densities needed to describe such processes:



GPDs depend on x, ξ, t, Q^2

convenient: symmetric choice of mom. fractions

- x, ξ: mom. fractions w.r.t. $P \equiv \frac{1}{2}(p+p')$

  where $\xi = (p-p')^+/(p+p')^+$

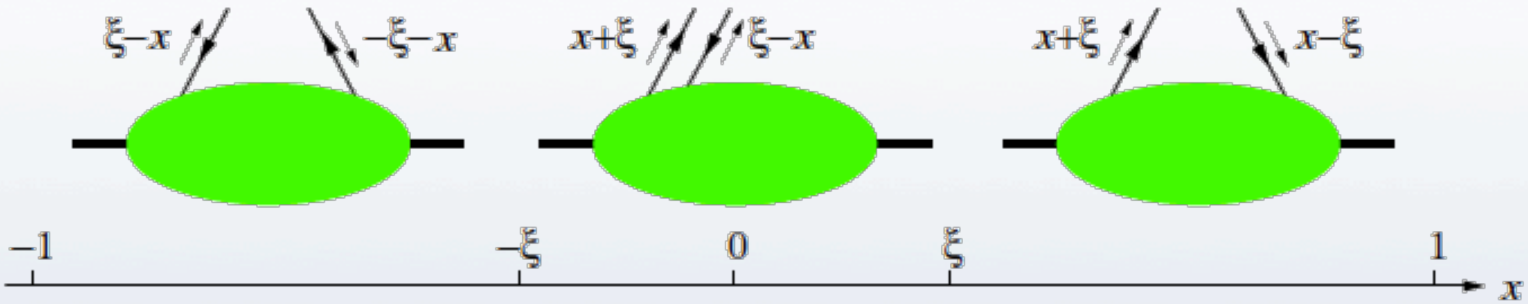
  in DVCS: x integrated and $\xi = x_B/(2-x_B)$

- t: trade for trans. momentum transfer Δ

- GPDs represent interference between amplitudes for different nucleon states (in general not a probability)

GPDs: some important properties

- distinguish two kinematical regimes:



probes emission of mesonic d.o.f.

no PDF counterpart

partons emitted and reabsorbed

reduce to PDFs in forward limit

- 4 GPDs per flavor: $H^i(x,\xi,t,Q^2), E^i(x,\xi,t,Q^2), \tilde{H}^i(x,\xi,t,Q^2), \tilde{E}^i(x,\xi,t,Q^2)$

unpolarized partons — polarized partons

e.g. $$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p', s' | \bar{q}(-\frac{z}{2})\, \mathcal{W}\, \gamma^+ q(\frac{z}{2}) | p, s\rangle_{z^+=0,\mathbf{z}=\mathbf{0}}$$

$$= \quad H^q\, \bar{u}(p',s')\gamma^+ u(p,s) + E^q\, \bar{u}(p',s')\frac{i}{2m_p}\sigma^{+\alpha}(p'-p)_\alpha u(p,s)$$

recover quark PDFs for $s=s', \xi=0, t=0$

decouples for p = p'; involves helicity flip

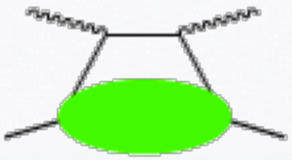
-> indicator of OAM, key part of Ji sum rule

transverse imaging through GPDs

initial studies (stage 1):

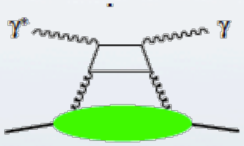
• find for DVCS amplitude at LO approximation:

$$\mathcal{H} = \sum_q e_q^2 \int_{-1}^{1} dx \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right] H^q(x, \xi, t, Q^2)$$



--> imaginary part determines H(x,ξ=x,t) at "cross over line"

at NLO: access also DGLAP region |x| ≥ ξ and gluon GPD



• measure its t dependence and Fourier transform to impact parameter space

$$F(b) = \frac{1}{(2\pi)^2} \int d^2\mathbf{\Delta} e^{-i\mathbf{\Delta b}} \sqrt{\frac{d\sigma}{dt}} = \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

[$t = -\Delta^2$]

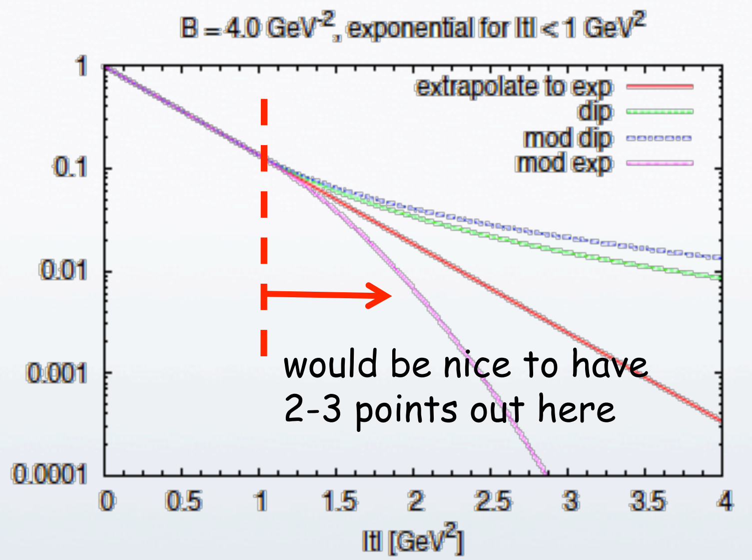
• **challenge:** cannot measure for arbitrary large or very small Δ

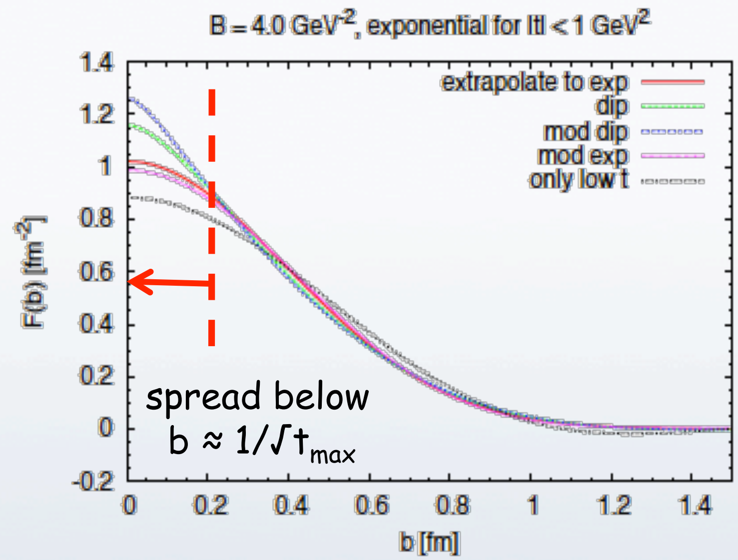
- what range in t (or Δ) do we need to limit extrapolation uncertainties ?
- experimental feasibility & requirements: good t resolution, guarantee exclusivity
  (need to integrate Roman pots into design to detect low p_T protons)

imaging through GPDs - required t-range

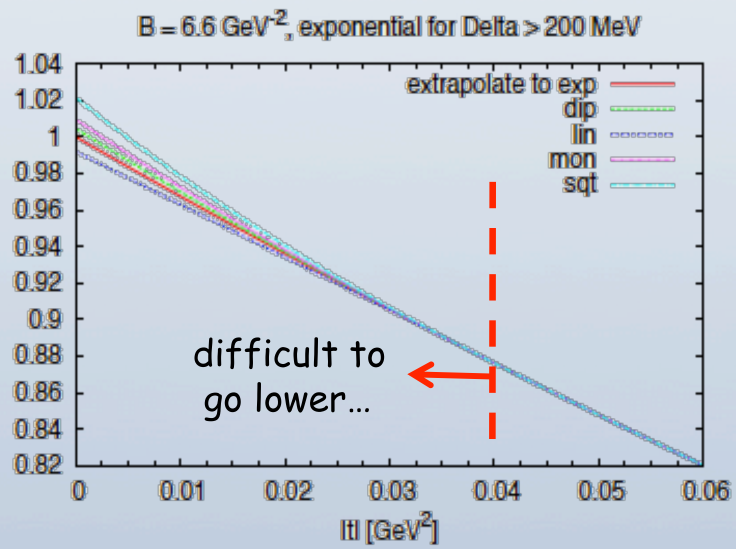
extrapolation uncertainty from **large t** and its impact on **small b**:

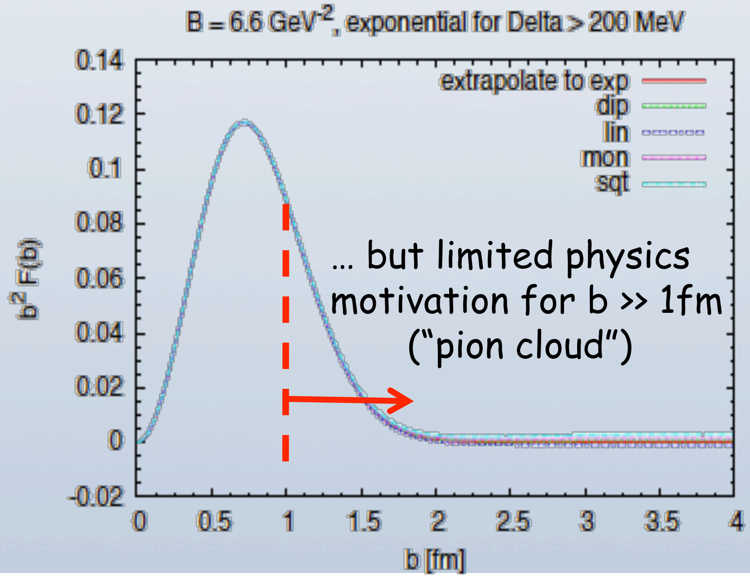
M. Diehl



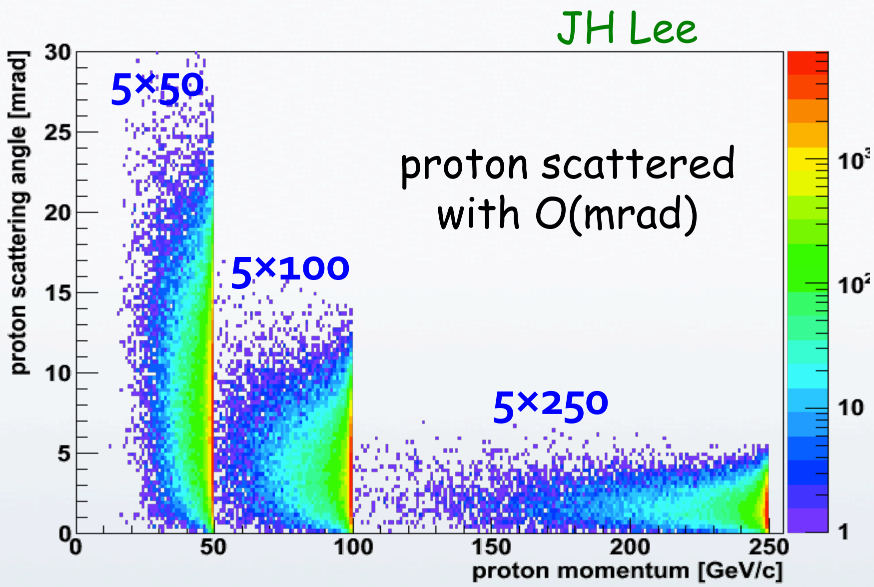


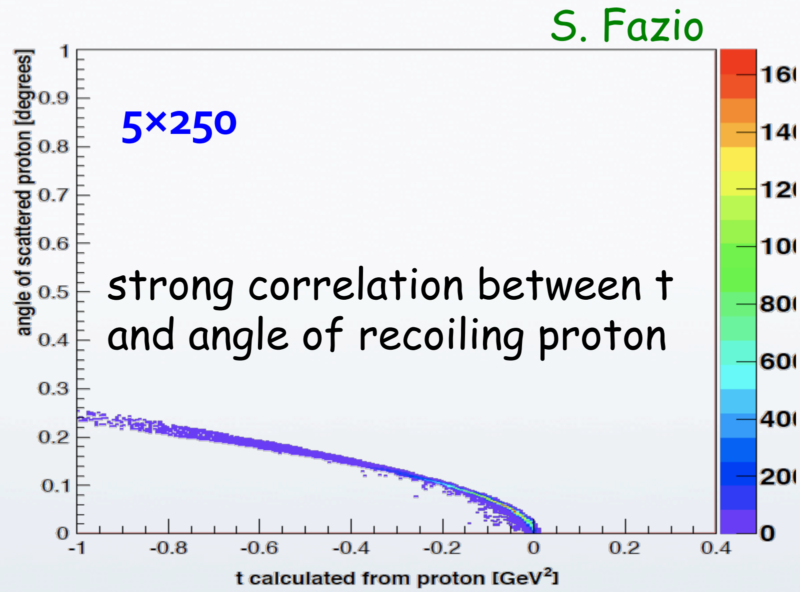
extrapolation uncertainty from **small t** and its impact on **large b**:





imaging through GPDs – some experimental aspects



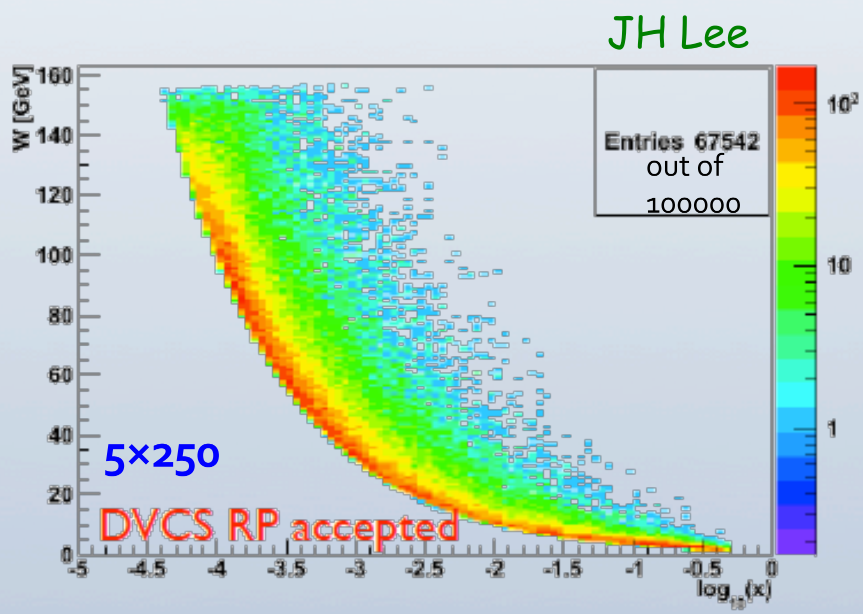


- large t acceptance
  vs magnet aperture

- small t acceptance
  vs beam size

- need to integrate
  Roman pots

- challenging IR design



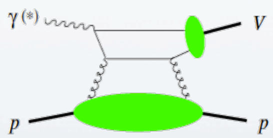
imaging through GPDs - ultimate goal

- reconstruct full ξ dependence of GPDs from Q^2 evolution / scaling violations

  global analysis framework already in place (used to analyze HERA data)
  Muller, Kumericki, Passek-Kumericki

  need to study how strongly extrapolation to ξ=0 will depend on assumptions

- detailed studies of exclusive vector meson production



- perform Fourier transformation for GPDs at ξ=0

e.g. $q(x, b^2) \simeq \int d^2\mathbf{\Delta} e^{-ib\mathbf{\Delta}} H^q(x, \xi = 0, t = -\mathbf{\Delta}^2)$ where $\mathbf{\Delta} = p' - p$

gives distribution of quarks with

- longitudinal momentum fraction x
- transverse distance b from proton center

- connection to energy-momentum tensor & OAM: $\frac{1}{2}\int dx x(H^q + E^q) = J^q(t)$

- GPDs contain form factors and PDFs (in certain limits)

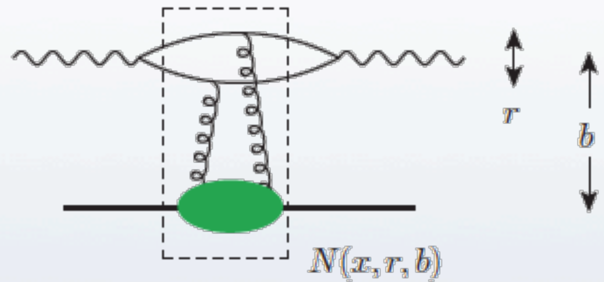
$$\int_{-1}^{1} dx \{H, E, \tilde{H}, \tilde{E}\} \qquad s = s', \xi = 0, t = 0$$

aside: color dipole model

describes variety of ep processes at **small x** in an alternative framework
(inclusive DIS; inclusive diffraction; exclusive processes)

underlying physical picture:

DIS in the proton rest frame can be viewed as the photon splitting into a quark-antiquark pair ("**color dipole**") which scatters off the proton (= "slow" gluon field)



- FT links rel. transverse momentum to transverse distance r of color dipole
- empirically valid for x below about 0.01
- t dependence: exp(-b|t|); b = trans. dist. of colliding objects
- phenomenological models for dipole cross section, e.g., Wusthoff, Golec-Biernat

comparison to GPD "language":

- dipole: specific representation of k_T factorization, predicts small x behavior at fixed Q^2
- GPD: predicts Q^2 dependence for all x (in large Q^2 limit)
- equivalent in "double limit": small x and high Q^2

Heavy Flavors

treatment of heavy quarks

(= getting used to acronyms)

heavy quarks: $m_Q \gg \Lambda_{QCD}$ (i.e., charm, bottom, top)

- no mass singularities -> no evolving, genuine heavy quark PDFs
- asymptotically large logarithms in DIS $\sim \ln Q/m_Q$

different ways to treat heavy quarks in calculations: (use charm in DIS as an example)

- $Q \not\gg m_c$ fixed flavor-number scheme FFNS

  only u, d, s, g are active partons; charm produced though $\gamma^* g \to c\bar{c}$

  NLO parton-level MC (HVQDIS) Harris, Smith

- $Q \ggg m_c$ zero mass variable flavor-number scheme ZM-VFNS

  standard evolution with massless partons above "threshold" $Q = m_c$

- $Q \gg m_c$ general mass variable flavor-number scheme GM-VFNS

  attempt to match two *distinct* theories (n_f=3+m_c vs. n_f=4)

  needs some matching & "interpolating" coefficient fcts.

  details matter in global fits !

not a priori clear if / where logs matter

treatment of heavy quarks - cont'd

each PDF group has its own favorite scheme:

CTEQ: ACOT, ACOT-χ, S-ACOT, S-ACOT-χ; MSTW: TR, TR'; NNPDF: FONLL; ABKM: BMSN

but VFNS must be derived from FFNS: relations between n_f and n_f+1 partons

Buza, Matiounine, Smith, van Neerven; Bierenbaum, Blümlein, Klein; ....

BMSN construction for F_2^{charm} : (used by Alekhin, Blümlein, Klein, Moch)

$$F_2^c(n_f+1,x,Q^2) \quad = \quad F_2^{c,FFNS}(n_f,x,Q^2) + F_2^{c,ZMVFNS}(n_f+1,x,Q^2) - F_2^{c,asym}(n_f,x,Q^2)$$

exact massive part
$m_c \neq 0$

zero mass part
$m_c = 0$
ln Q/m_c resummed

asymptotic part
ln Q/m

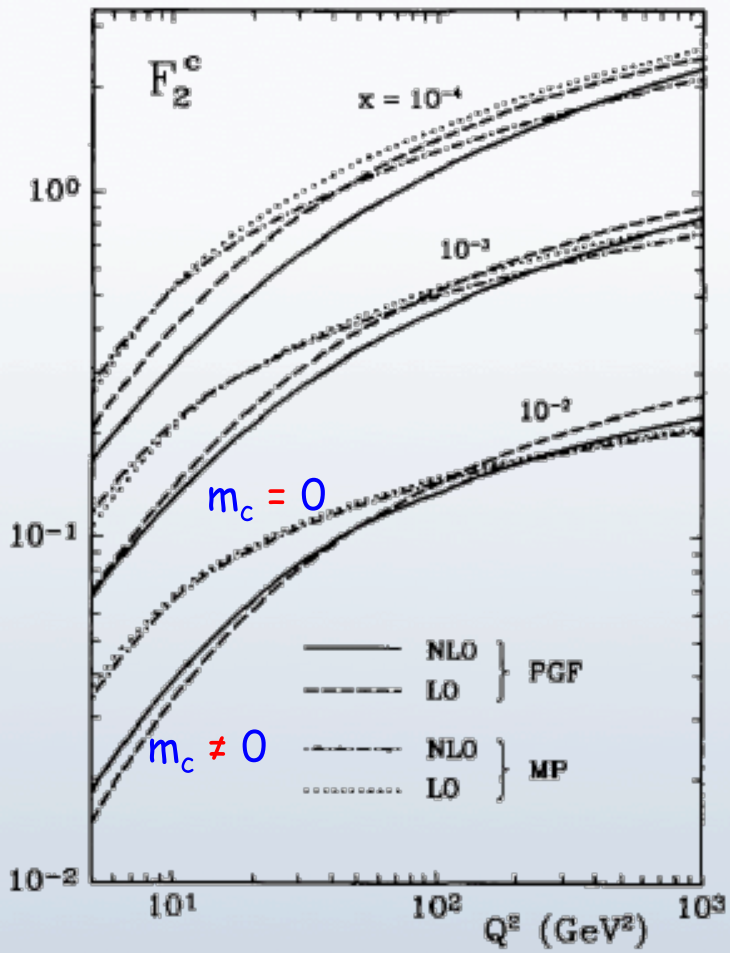
another issue: quark masses in PDF fits

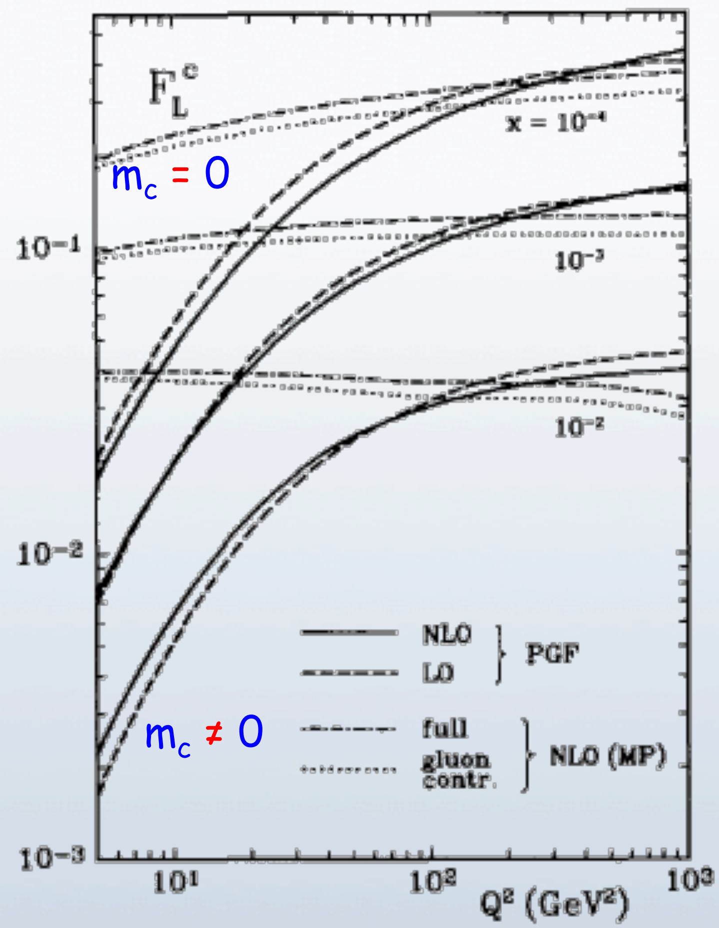
- choice of m_c part of uncertainty
- all fits use pole mass so far
- consistently lower than PDG value
- latest: running mass in DIS fits Alekhin, Moch
  find $m_c(m_c)$ = 1.01 ± 0.09(exp) ± 0.03(th)

	m_c [GeV]
ABKM	1.43±0.1
MSTW	1.40
CTEQ 6.6	1.30
PDG	1.66+0.09-0.15

heavy quarks – do they ever become “light“ ??

long-standing question ... (example from ‘94 Glück, Reya, MS)





- even at high Q^2 or W^2, $m_c = 0$ approx. not effective
- no smooth transition/matching
- existing HERA data described well with $m_c \neq 0$

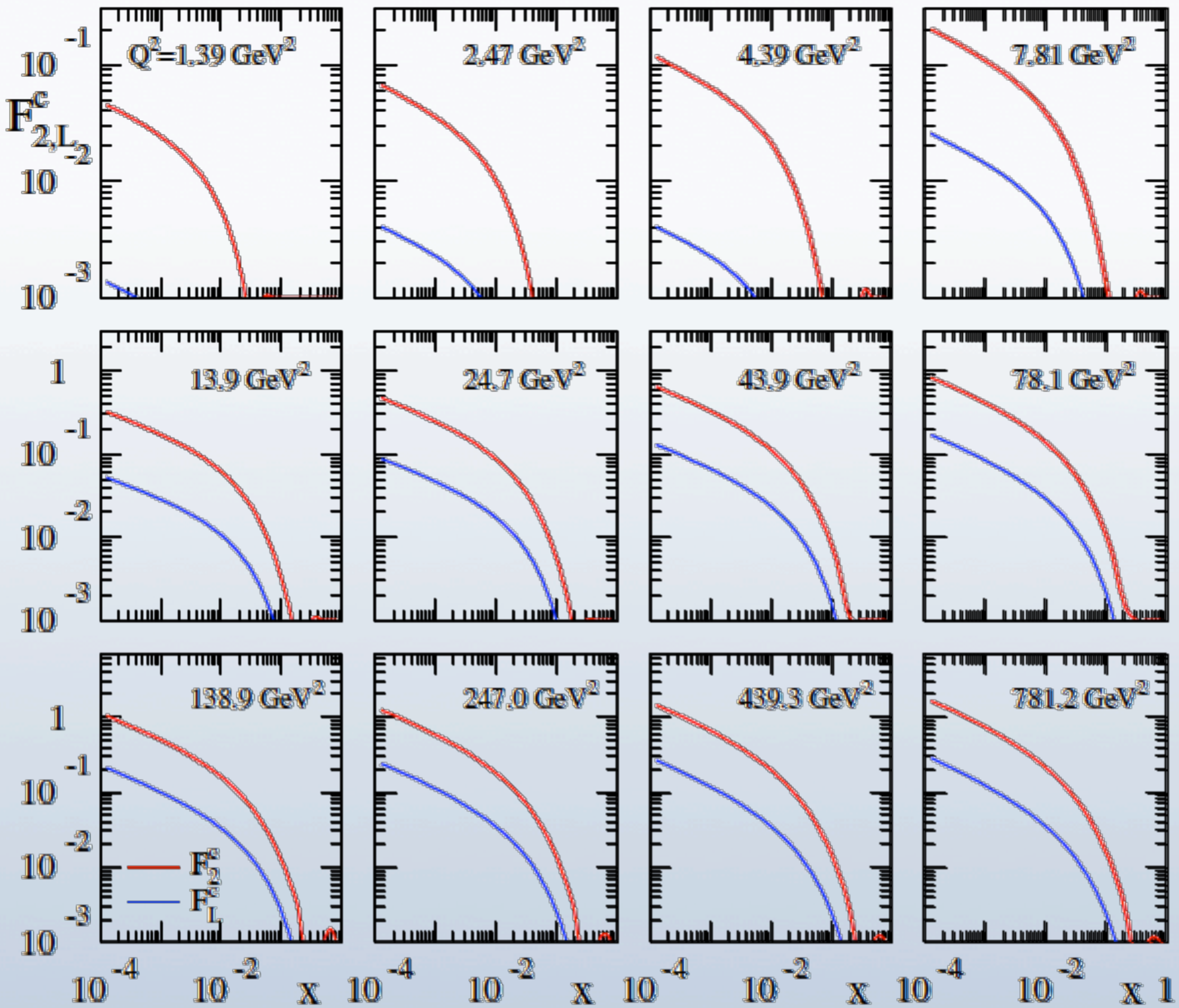
- differences more dramatic for F_L^c

never measured

target for eRHIC

expectations for F_2^c and F_L^c

ABKM (S. Alekhin)



- shown:

  F_2^c BMSN

  (close to $m_c \neq 0$)

- F_L^c is not small

  ($m_c \neq 0$)

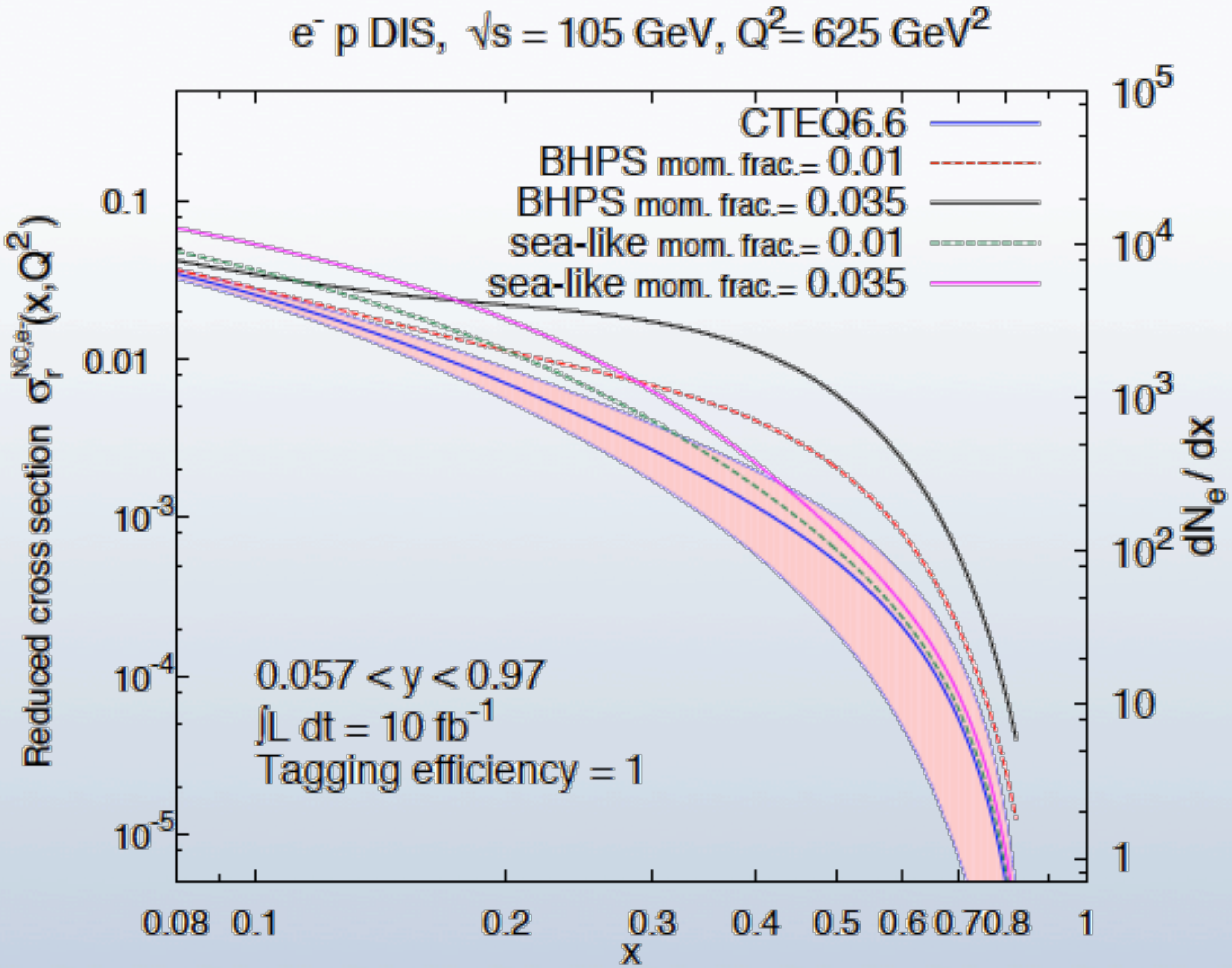
TO DO:

det. simulations & optimize extraction of $F_{2,L}^c$

intrinsic charm ?

Brodsky, Hoyer,
Peterson, Sakai

can we finally settle this?

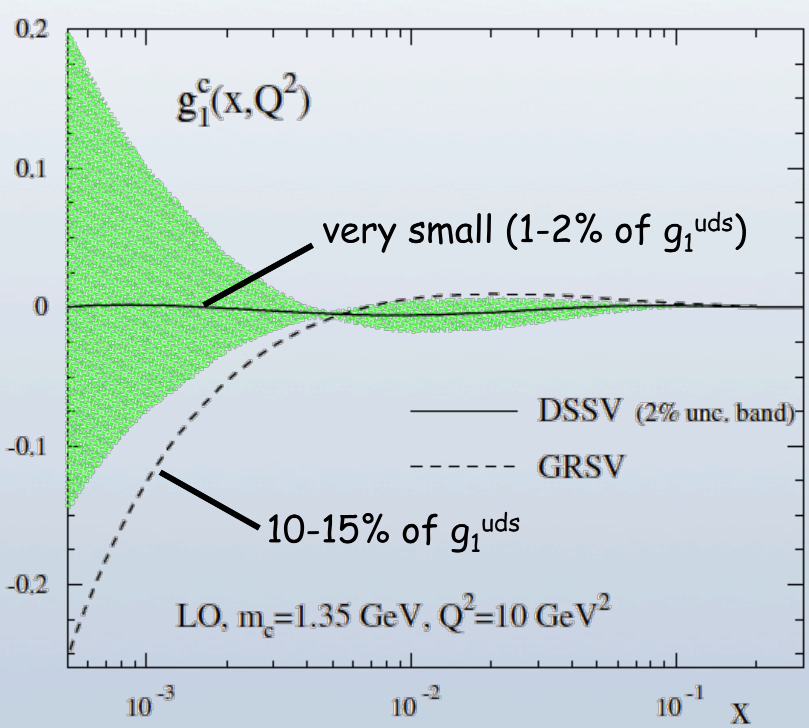


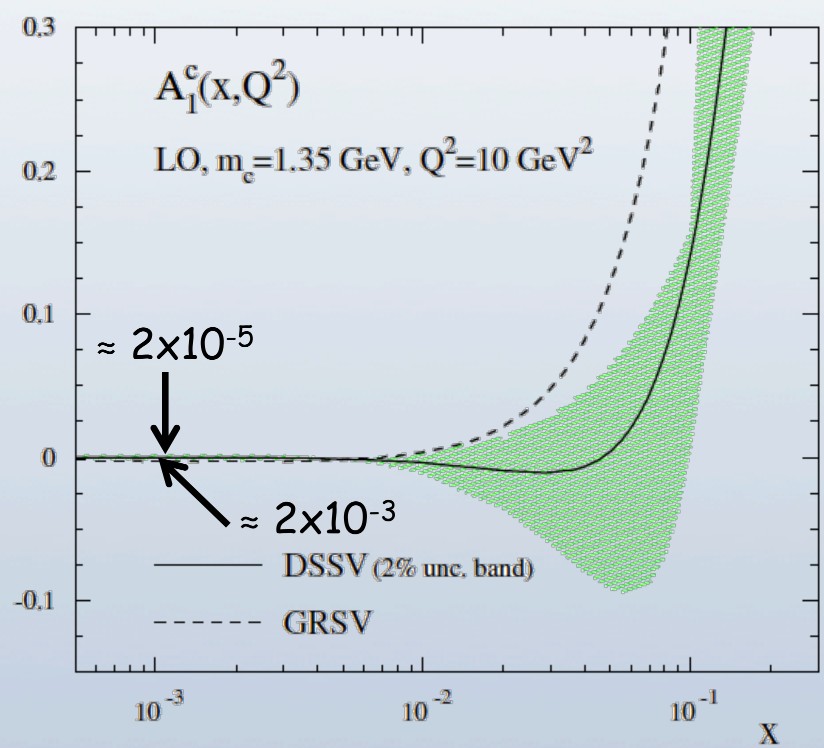
M. Guzzi, P. Nadolsky, F. Olness (work in progress)

charm contribution to pol. DIS: g_1^c

- so far safely ignored: « 1% to existing g_1 fixed-target data
- numerical relevance at eRHIC depends strongly on size of Δg
- need massive Wilson coefficients (charm not massless for most of eRHIC kinematics)
  so far only known to LO (NLO is work in progress Kang, MS)

some expectations: (need to be studied in detail)





PHOTOPRODUCTION

main objective / why interesting

- make use of bulk of events sitting at low Q^2
- access to non-perturbative structure of photons

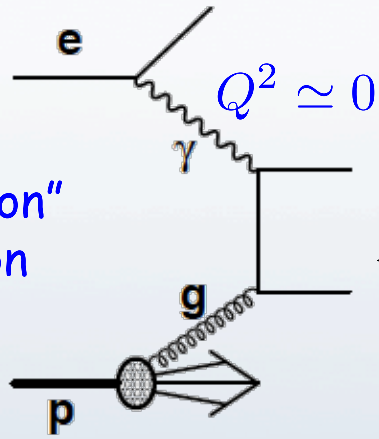
why should I bother about yet ***another*** non perturbative function ?

- needed for consistent factorization in all processes with quasi-real photons
- ILC has a program for $\gamma\gamma$ physics perhaps even with polarization
- unpolarized photon structure not well known: LEP $\gamma^*\gamma$ DIS, some HERA data
  (a global analysis was never performed; no error estimates)
- polarized photon structure is completely unknown
- non-trivial inhomogeneous Q^2 evolution
  (due to pointlike coupling of photons to quarks)
- pQCD framework more involved than for DIS-type processes

photoproduction basics

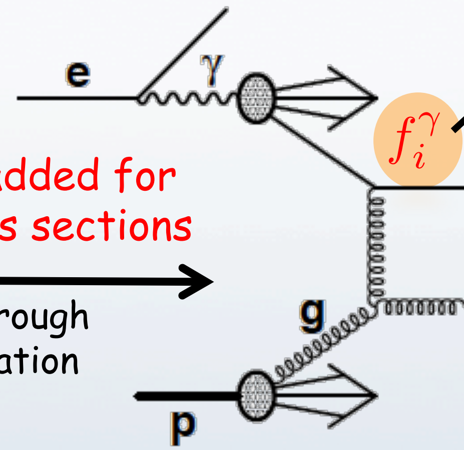
cross sections consist of two contributions, e.g. at $\mathcal{O}(\alpha\alpha_s)$

"direct photon" contribution



need to be added for physical cross sections

linked through factorization



parametrically of $\mathcal{O}(\alpha/\alpha_s)$

"resolved photon" contribution

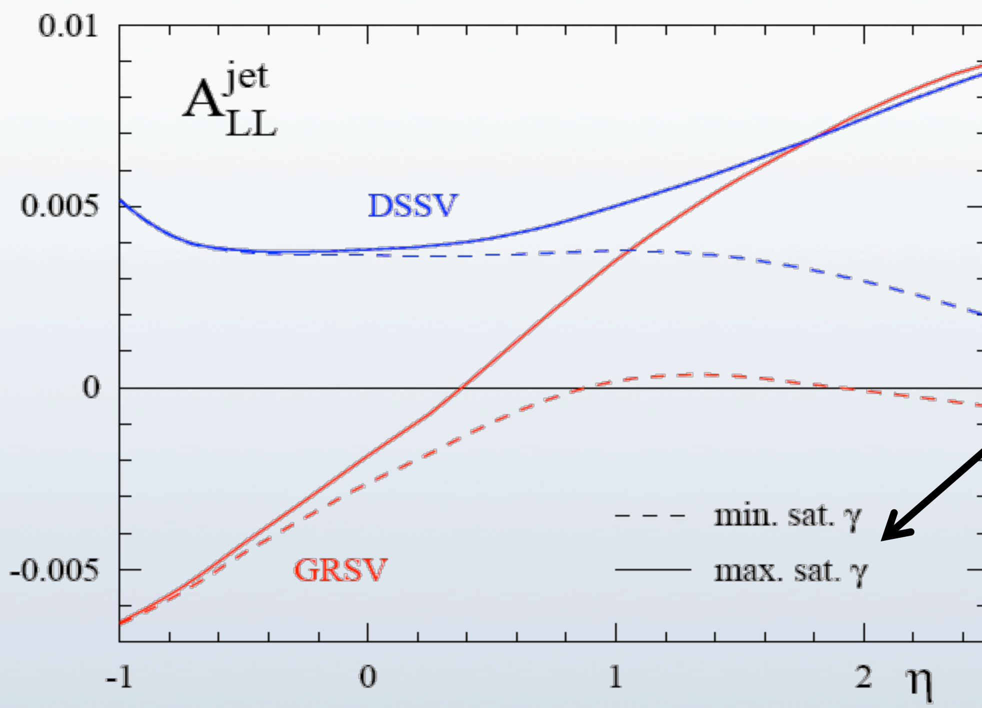
$$d\sigma_{dir} = d\hat{\sigma}_{\gamma j \to kl} \otimes f_j^p \qquad d\sigma_{res} = d\hat{\sigma}_{ij \to kl} \otimes f_i^\gamma \otimes f_j^p$$

- most processes of interest (charm, hadrons, jets, photons) are known to NLO (pol+unp)
- strategies to enhance sensitivity to resolved part known from HERA:
  - single-inclusive: need to look into rapidity dependence
  - di-jets: can define resolved sample (LO only) $x_\gamma^{obs} = \dfrac{E_T^{jet1} e^{-\eta^{jet1}} + E_T^{jet2} e^{-\eta^{jet2}}}{2yE_e}$

example I: inclusive jets (or hadrons)

- polarized photon structure from 1-jet production
  (very similar: 1-hadron production Jäger, MS, Vogelsang)

TO DO:
simulations &
estimate uncertainties



p_T^{jet} > 4 GeV

10x250 GeV

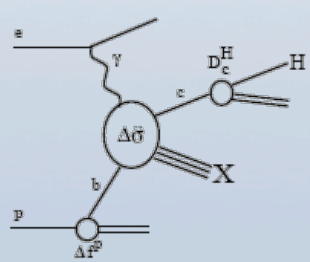
1-jet

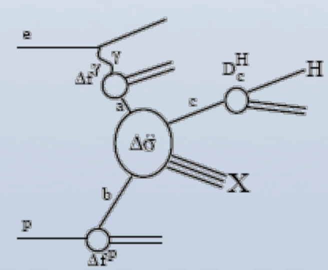
Jäger
arXiv:0807.0066

different
assumptions
about Δf^{γ}

lepton ⟵ ⟶ **proton**

$x_\gamma \approx 1$
probes proton PDFs





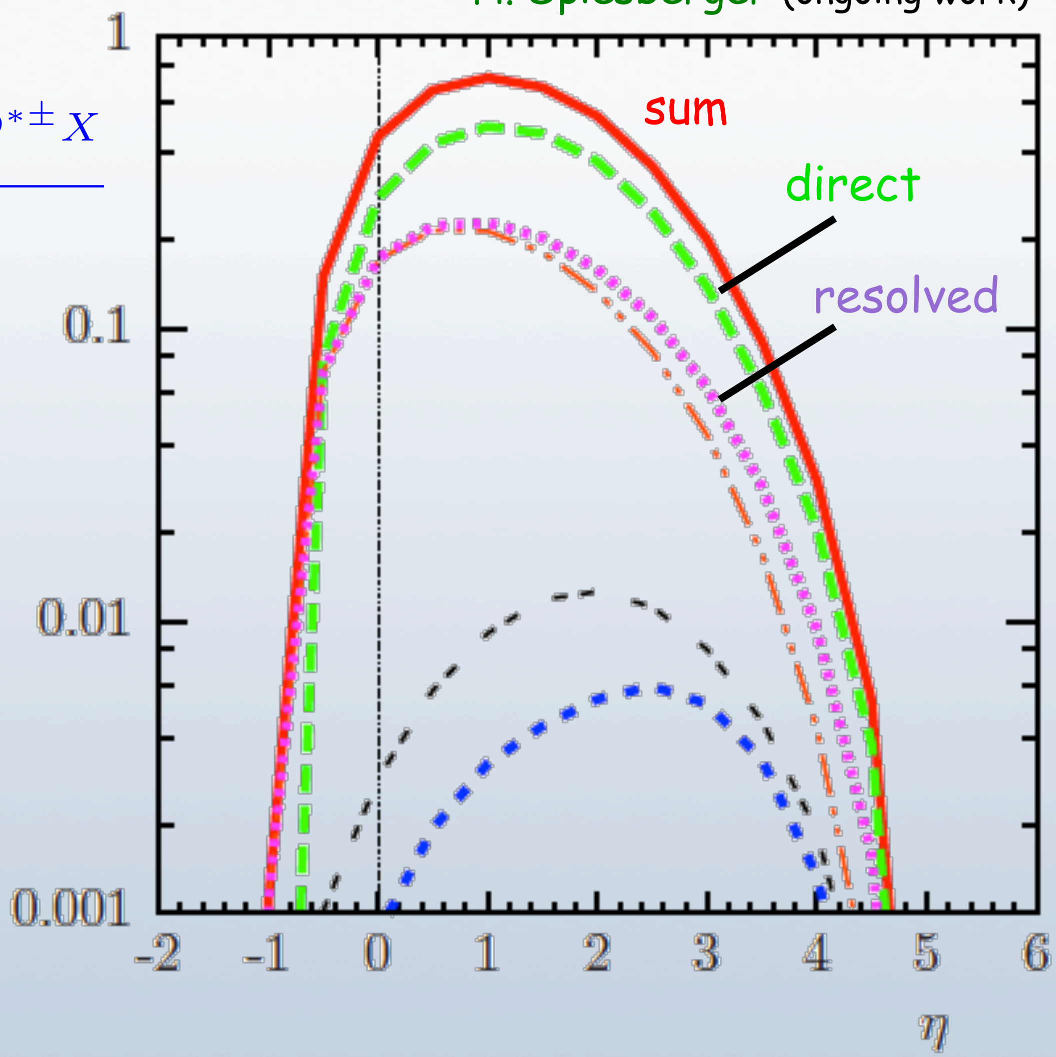
$x_\gamma \ll 1$
probes unknown
photon PDFs

example II: charm

- unpolarized photoproduction of charm

H. Spiesberger (ongoing work)

$$\frac{d\sigma^{\gamma p \to D^{*\pm} X}}{d\eta}$$



5×325 GeV

3 < p_T < 5 GeV

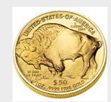
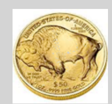
Summary
"Golden PDF Measurements"

we have made quite some progress in making the science case for eRHIC

several unique measurements have been identified:

- excellent prospects to determine $\Delta g(x)$ from scaling violations in DIS
- full flavor separation of quark sea in large x,Q^2 range from SIDIS
- novel electroweak probes of polarized PDFs & electroweak precision tests
- 3D imaging of the proton through TMDs and GPDs incl. sea quarks and gluons
- understand the treatment of heavy quarks (F_2, F_L, ...)
- explore processes involving photons in great detail

report of the INT workshop will appear in a few weeks on the arXiv

Science Deliverable	**Basic Measurement**	**Uniqueness Feasibility Relevance**	**Requirements**
spin structure at small x contribution of Δg, $\Delta\Sigma$ to spin sum rule	inclusive DIS	✔ 	minimal large x,Q^2 coverage about 10fb^{-1}
full flavor separation in large x,Q^2 range strangeness, $s(x)$-$\bar{s}(x)$ polarized sea	semi-inclusive DIS	✔ 	very similar to DIS excellent particle ID improved FFs (Belle,LHC,...)
electroweak probes of proton structure flavor separation electroweak parameters	inclusive DIS at high Q^2	✔  some unp. results from HERA	20x250 to 30x325 positron beam ? polarized ^{3}He beam ?
spatial structure down to small x through TMDs and GPDs	SIDIS azim. asym. & exclusive processes	✔  some results in valence region	p_T^H binning, t resolution, exclusivity, Roman pots, large (x,Q^2) range